

Mobile Graphics

Siggraph Asia 2017 course

Marco Agus, KAUST & CRS4

Enrico Gobbetti, CRS4

Fabio Marton, CRS4

Giovanni Pintore, CRS4

Pere-Pau Vázquez, UPC

November 2017



WELCOME TO THIS HALF-DAY COURSE!

Subject: Mobile Graphics

- **All you need to know to get an introduction to the field of mobile graphics:**
 - Scope and definition of “mobile graphics”
 - Brief overview of current trends in terms of available hardware architectures and research apps built on top of them
 - Quick overview of development environments
 - Rendering, with focus on rendering massive/complex surface and volume models
 - Capture, with focus on data fusion techniques

Speakers (in alphabetical order)

- **Marco Agus (1,2)**
 - Research Engineer at KAUST (Saudi Arabia)
 - Researcher at CRS4 (Italy)
- **Enrico Gobbetti (1) - Organizer**
 - Director of Visual Computing at CRS4 (Italy)
- **Fabio Marton (1)**
 - Researcher at CRS4
- **Giovanni Pintore (1)**
 - Researcher at CRS4
- **Pere-Pau Vázquez (3)**
 - Professor at UPC, Spain

(1) www.crs4.it/vic/

(2) <https://vcc.kaust.edu.sa>

(3) <http://www.virvig.eu/>



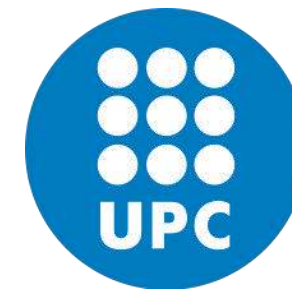
Funding



**Center for Research,
Development, and Advanced
Studies in Sardinia, Italy**



**King Abdullah University
of Science & Technology,
Saudi Arabia**



**Polytechnic University of
Catalonia,
Spain**



**Project TDM
RAS - POR FESR 2014-2020**



**REGIONE AUTONOMA DE SARDIGNA
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Projects VIGEC / VIDEOLAB**



**Spanish MINECO Ministry
FEDER funds
Grant No. TIN2014-52211-C2-1-R**

Schedule

5'	0. Introduction and outline	Enrico
15'	1. Evolution of Mobile Graphics	Marco
20'	2.1 Mobile Graphics Trends / Hardware	Pere-Pau
15'	2.2 Mobile Graphics Trends / Applications	Marco
15'	3. Graphics Development for Mobile Systems	Marco
5'	4.1 Scalable Mobile Visualization / Introduction	Enrico
30'	4.2 Scalable Mobile Visualization / Massive Meshes	Fabio
15'	BREAK	-
5'	4.3 Scalable Mobile Visualization / Intro to complex lighting	Enrico
10'	4.4 Scalable Mobile Visualization / Lighting Precomputation	Fabio
20'	4.5 Scalable Mobile Visualization / Smart Shading	Pere-Pau
15'	4.6 Scalable Mobile Visualization / Volumes	Pere-Pau
10'	5.1 Mobile Metric Capture and Reconstruction / Introduction	Enrico
30'	5.2 Mobile Metric Capture and Reconstruction / Case studies	Gianni
15'	6. Closing and Q&A	ALL

Next Session

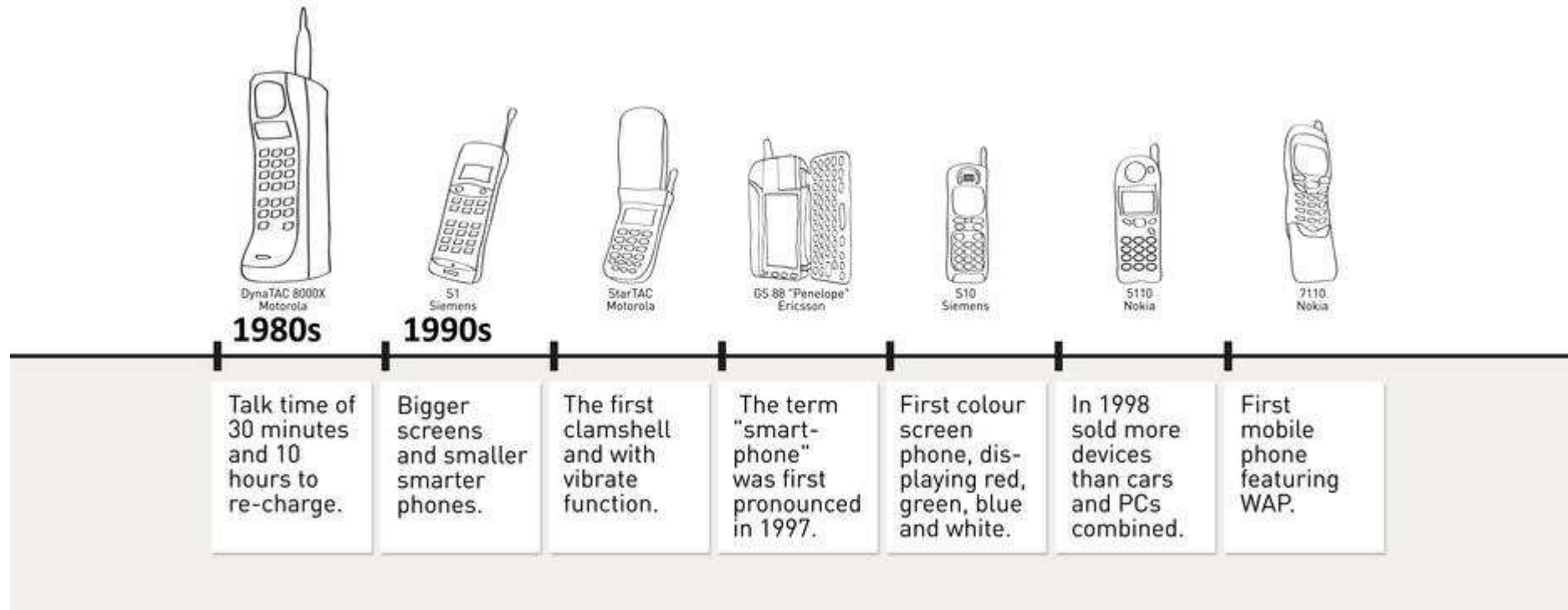
EVOLUTION OF MOBILE GRAPHICS

Part 1

Evolution of the mobile graphics world

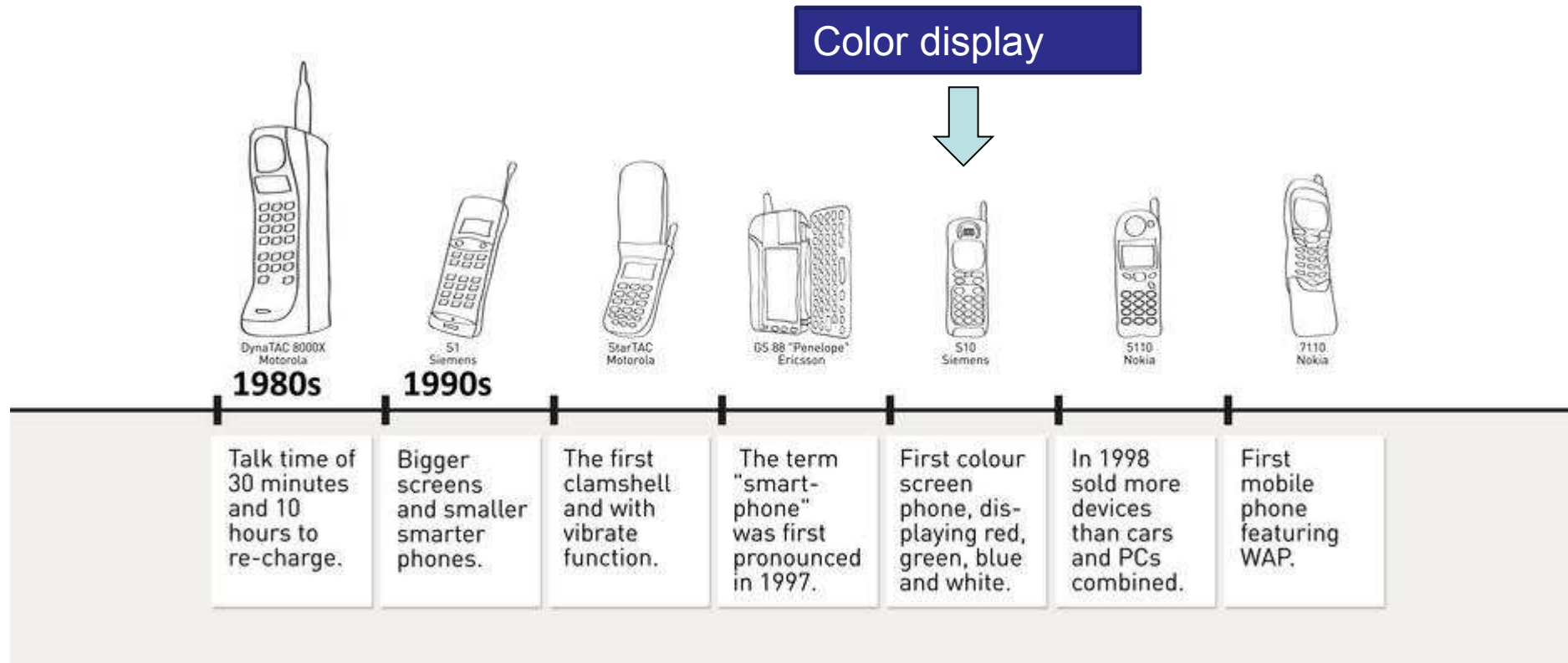
Marco Agus, KAUST & CRS4

Mobile evolution (1/3)



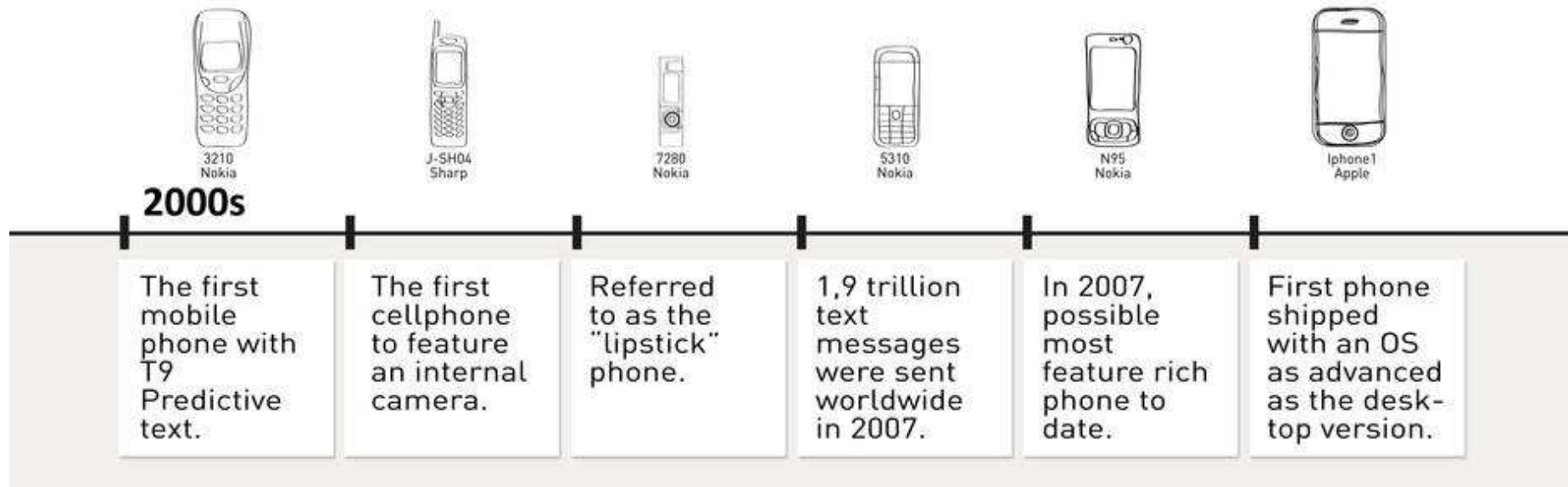
Infographic designed by LEWIS
PR for Mobile World Barcelona

Mobile evolution (1/3)



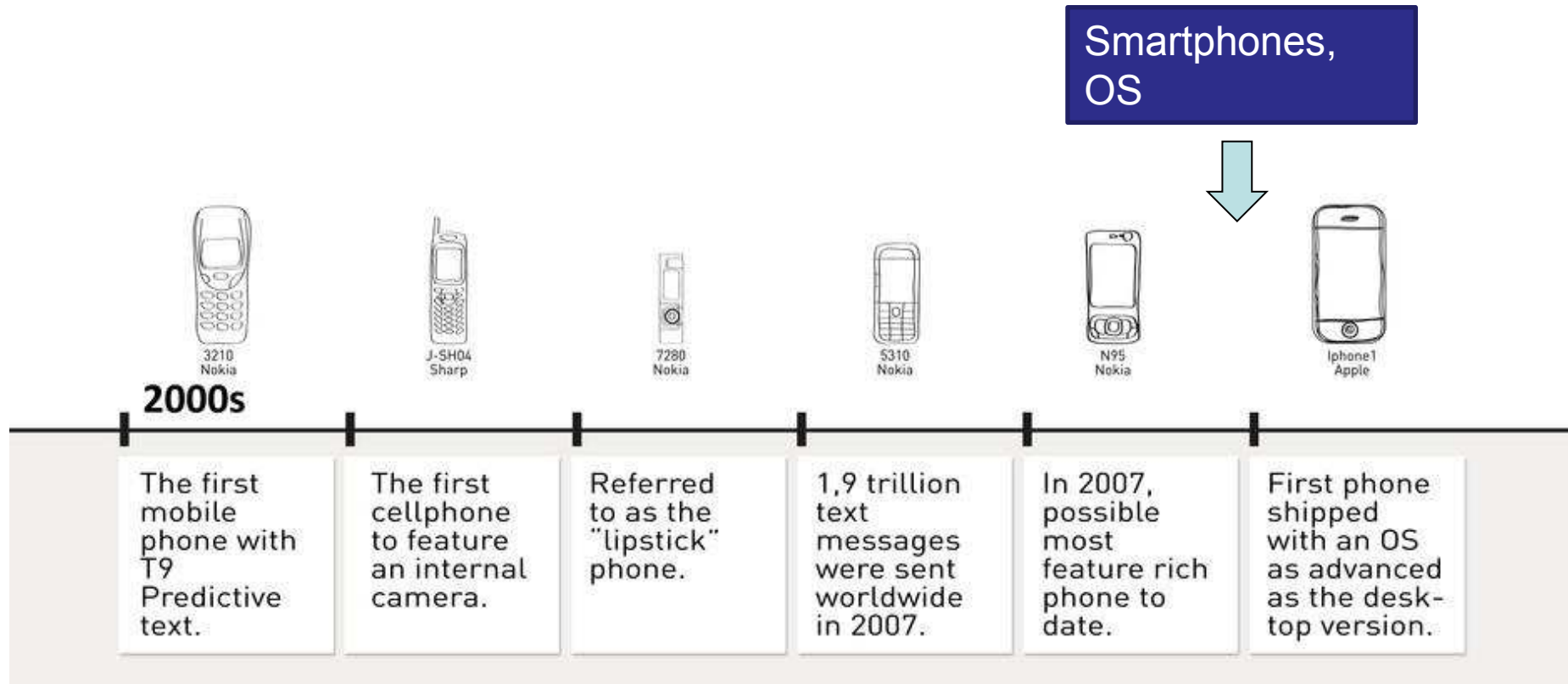
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Mobile evolution (2/3)



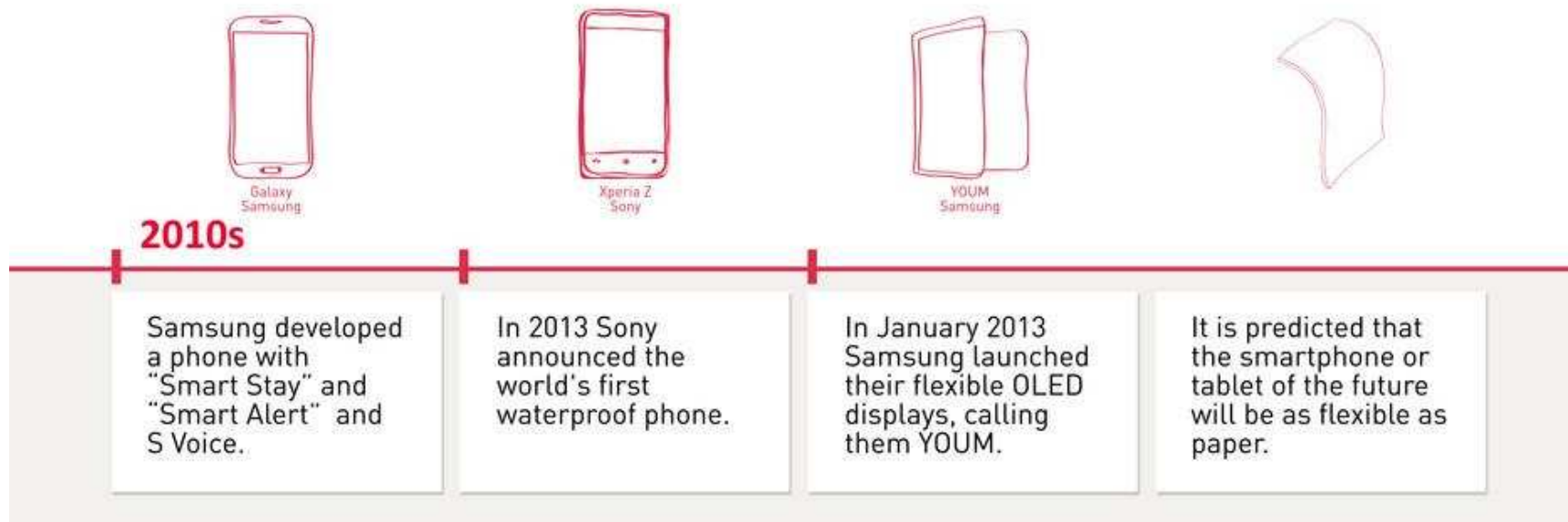
Infographic designed by LEWIS
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Mobile evolution (2/3)



Infographic designed by LEWIS
PR for Mobile World Barcelona

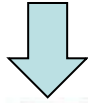
Mobile evolution (3/3)



Infographic designed by LEWIS
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Mobile evolution (3/3)

High resolution
displays

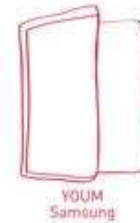


2010s

Samsung developed a phone with "Smart Stay" and "Smart Alert" and S Voice.



In 2013 Sony announced the world's first waterproof phone.



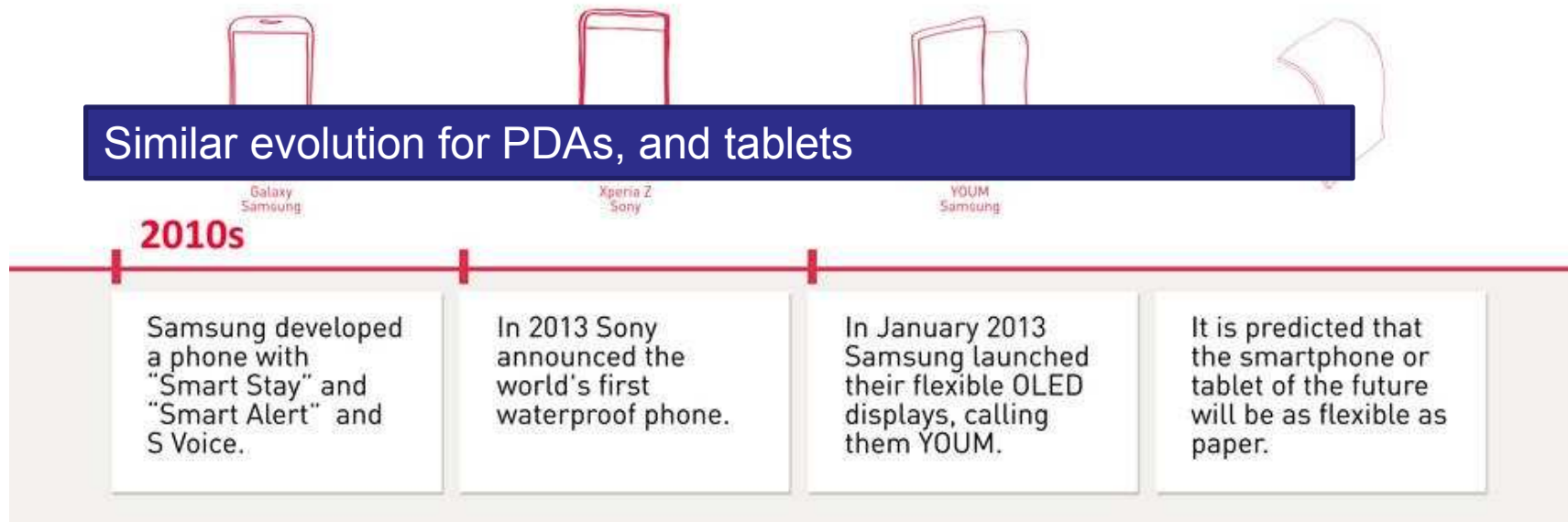
In January 2013 Samsung launched their flexible OLED displays, calling them YOUM.



It is predicted that the smartphone or tablet of the future will be as flexible as paper.

Infographic designed by LEWIS
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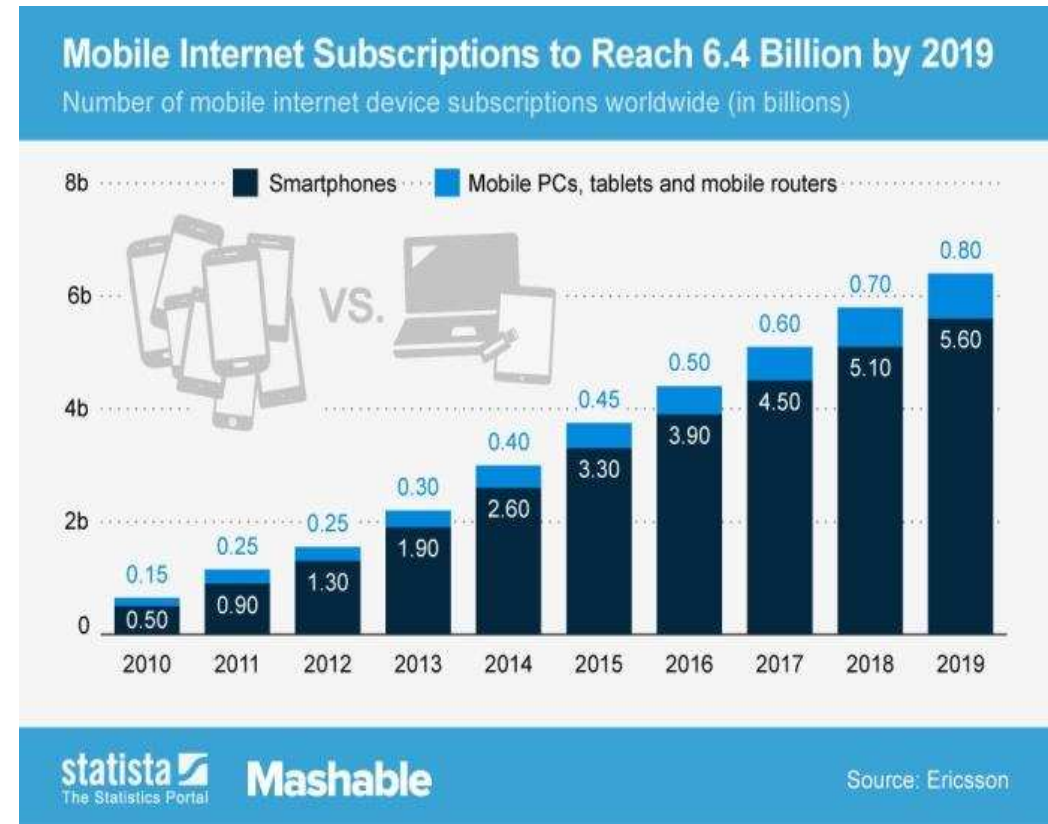
Mobile evolution (3/3)



Infographic designed by LEWIS
PR for Mobile World Barcelona

Mobile connectivity evolution

- Bandwidth is doubling every 18 months
- Mobile internet users overcame desktop internet users
- 2017 smartphone traffic expected at 2.7 GB per person per month



© www.statista.com

Displays and User Interface

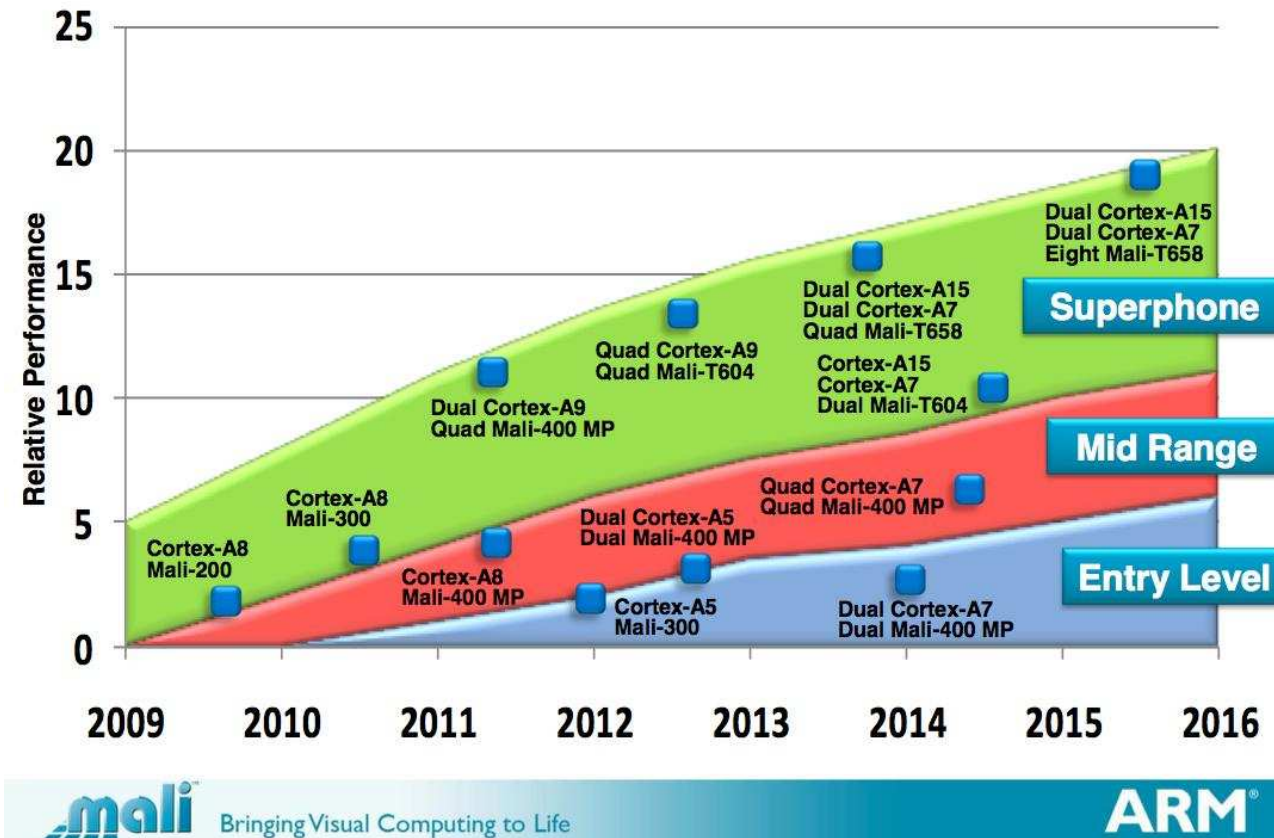
- **Before 2007 – old days**
 - PDA → Palm OS/ Windows Pocket / Windows CE
 - Stylus interaction (touch screens at early stages)
- **Touch era**
 - 2007 – iOS /iPhone
 - 2008 – Android / HTC Dream or G1
 - Touch-enabled devices (no stylus required)
- **Nowadays**
 - Wearables → <2”
 - Smartphones → 3-6”
 - Tablets → >7-10”
 - DLP projectors integrated

Display characteristics

	Application	100 PPI	150 PPI	200 PPI	250 PPI	300 PPI	400 PPI	500 ppi
20 cm	Smart Phone	3.5" 400 × 234 (132 PPI)	3.5" 480 × 320 (164 PPI)	→	3.5" 800 × 480 (266 PPI)	3.5" 960 × 640 (326 PPI)	3.5"/3.7" 1280 × 800 (400+ PPI)	5.1"/5.5" 2560x1440 (>500 PPI)
30 cm	Tablet PC	7" 800 × 480 (133 PPI) →	7" 1024 × 600 (169 PPI) →	7" 1280 × 800 1366 × 768 (215 PPI)				
		9.7" 1024 × 768 (132 PPI) →		9.7" 1600 × 1200 (206 PPI)	9.7" 2048 × 1536 (264 PPI)			
		10.1" 1024 × 600 (118 PPI) →	10.1" 1280 × 800 1366 × 768 (150 PPI)	10.1" 1920 × 1080 1920 × 1200 (210 PPI)	→	10.1" 2560 × 1600 (300 PPI)	10.1" 3840x2160 (438 PPI)	
40 cm	Mini-Note	10.1" 1024 × 600 (118 PPI)						
50 cm	Notebook PC	15.6" 1366 × 768 14.0" 1366 × 768 (110 PPI)						
60 cm	LCD MNT	21.5" 1920 × 1080 (100 PPI)						

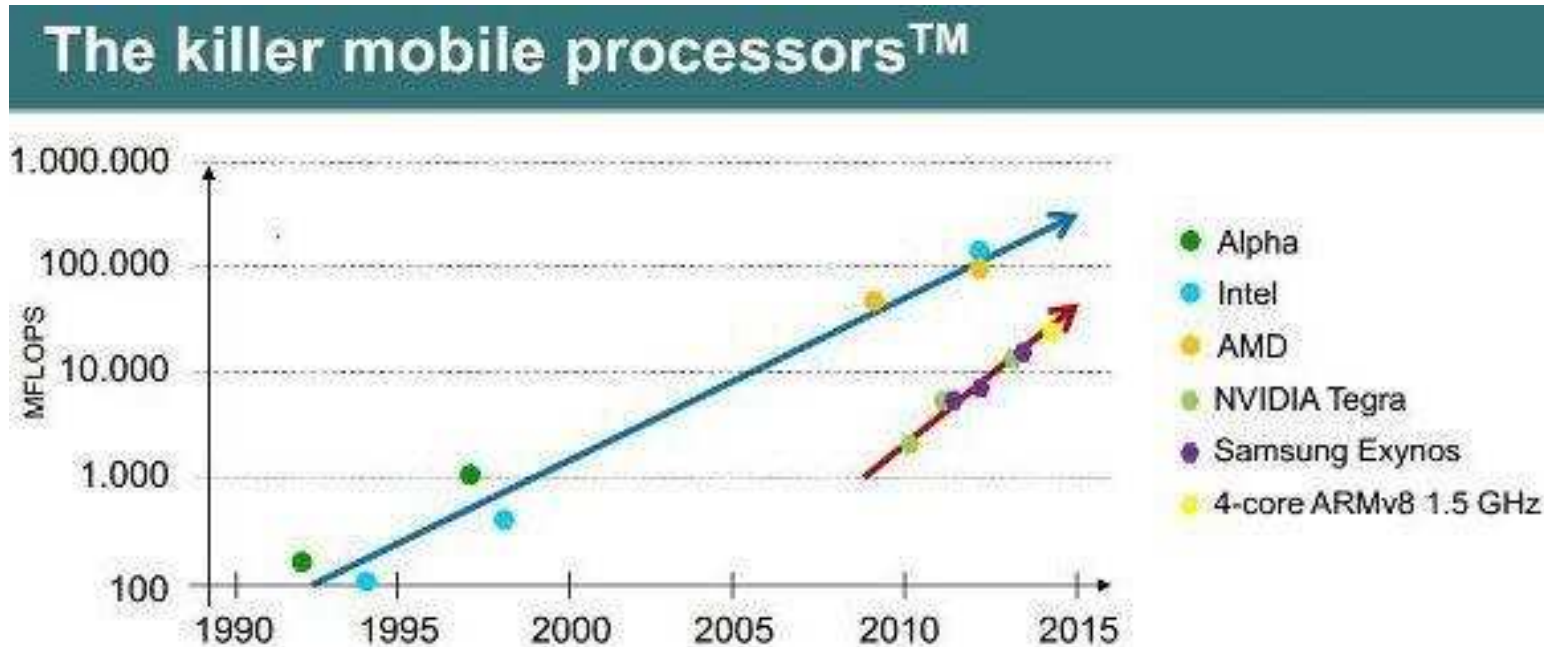
Chip evolution (1/2)

Scalable Mobile Processor Evolution



© ARM

Chip evolution (2/2)



- Microprocessors killed the Vector supercomputers
 - They were not faster ...
 - ... but they were significantly cheaper and greener

- History may be about to repeat itself ...
 - Mobile processor are not faster ...
 - ... but they are significantly cheaper

© Rajovic, N., Carpenter, P., Gelado, I., Puzovic, N., & Ramirez, A. (2013). Are mobile processors ready for HPC?. In Supercomput.

Scenario

- **Modern smartphones (tablets) are compact visual computing powerhouses**
- **DIFFUSION:** more than 4.6 billion mobile phone subscriptions
 - [Ellison 2010]
- **NETWORKING:** High speed internet connection (typical 1GB/month plan)
 - 3G - < 0.6-3Mbps ~ 100KB/s - 400KB/s (latency ~ 100-125ms)
 - 4G – < 3-10Mbps ~ 400KB/s - 1MB/s (latency ~ 60-70ms)
 - 5G - 1Gbps (from 2016?)
- **MEMORY:** Increasing RAM and storage space
 - RAM 1-3GB
 - Storage 8-64GB
- **COMPUTING:** Increasing processing power
 - CPU 4-8 core @ 2.5Ghz
 - GPU 72-192 cores (~ALUs)

Scenario

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Where are we going?

- **Powerful devices** for acquiring, processing and visualizing information
- **Accessibility of information** (anybody, any time, anywhere)
- **Immense potential** (integration of acquisition, processing, visualization, cloud computing, and collaborative tasks)

Next Session

MOBILE GRAPHICS TRENDS: HARDWARE ARCHITECTURES & APPLICATIONS

Part 2.1

Mobile Graphics Trends: Hardware Architectures

Pere-Pau Vázquez, UPC

MIPS

Mobile computing SoC

Power Management
MIPS CPU

Wi-Fi 802.11 and Bluetooth
MIPS CPU

GPS
MIPS CPU

2G/3G/4G
MIPS CPU

Clock/Reset
Interrupt Controller
Timers
Cluster Portbase

MIPS CPU 1
L1 Cache
L2 Cache

MIPS CPU n
L1 Cache
L2 Cache

PowerVR GPU
Cache

PowerVR VPU
Cache

Interconnect

Enigma GPU

Audio Engine (MIPS CPU)

SDRAM Controller
DDR3/DDR2/LPDDR3/LPDDR2 PHY

NAND/eMMC/SD Card controller

Multi-display system

Touchscreen

Camera

Flash storage

DMA

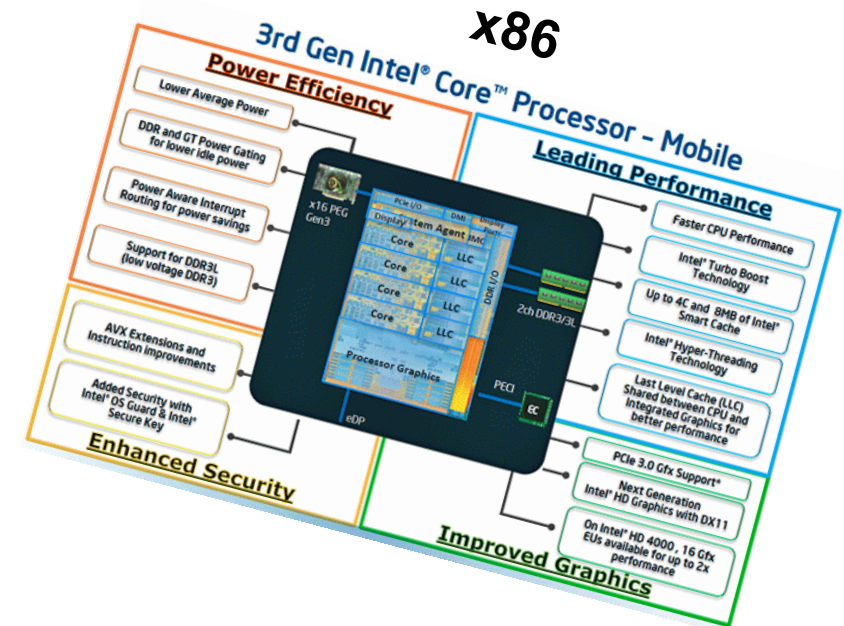
Crypto Engine
MIPS CPU

Boot ROM

SM Vt

HDMI Vt

PowerVR ISP



Architectures

- **x86 (CISC 32/64bit)**
 - Intel Atom Z3740/Z3770, X3/X5/X7
 - AMD Amur / Styx (announced)
 - Present in few smartphones, more common in tablets
 - Less efficient
- **ARM**
 - RISC 32/64bit
 - With SIMD add-ons
 - Most common chip for smartphones
 - More efficient & smaller area
- **MIPS**
 - RISC 32/64bit
 - Including some SIMD instructions
 - Acquired by Imagination, Inc. @2014

Architectures – RISC vs. CISC but...

- **CISC (Complex Instruction Set Computer)**
 - Fast program execution (optimized complex paths)
 - Complex instructions (i.e. memory-to-memory instructions)
- **RISC (Reduced Instruction Set Computer)**
 - Fast instructions (fixed cycles per instruction)
 - Simple instructions (fixed/reduced cost per instruction)
- **FISC (Fast Instruction Set Computer)**
 - Current RISC processors integrate many improvements from CISC: superscalar, branch prediction, SIMD, **out-of-order**
 - Philosophy → fixed/reduced cycle count/instr
 - Discussion (Post-RISC):
 - <http://archive.arstechnica.com/cpu/4q99/risc-cisc/rvc-5.html>

Landscape has changed a bit...

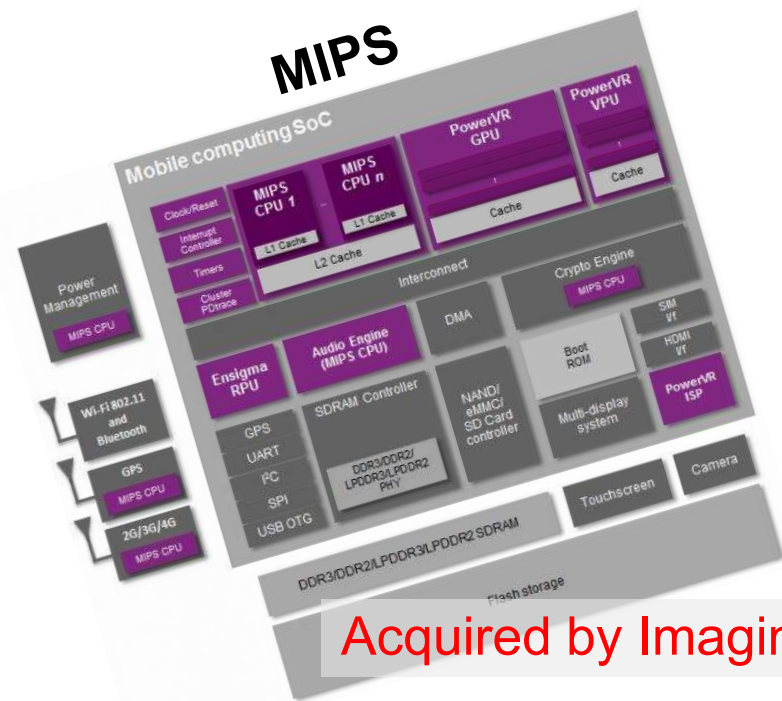
- **Status by 2014-2015:**

- Intel Atom X3/X5/X7 announced (March 2015)
- AMD announces Amur / Styx (20nm, Oct. 2014)
- Nvidia launches Tegra X1 (March 2015)
- ARM the only EU big technology company
- Imagination announces Furian (sub 14nm, March 2017) Imagination's chips are in iPhones & iPads

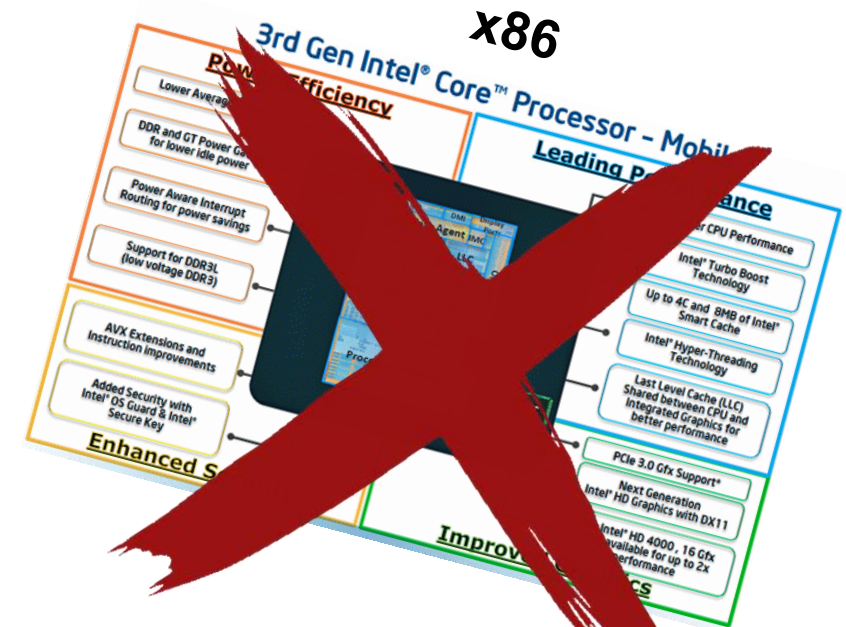
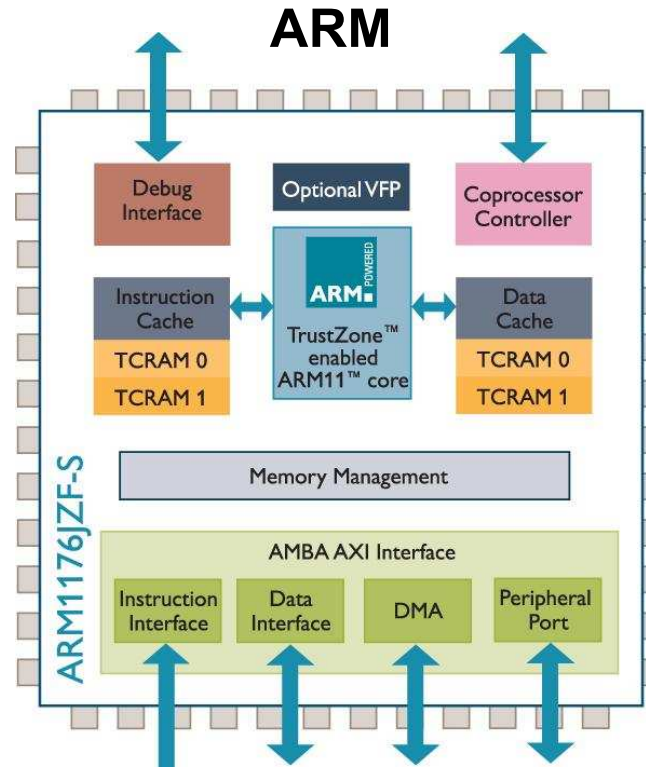
- **Nowadays:**

- Intel quits mobile Apr/May 2016
- AMD cancels 20nm chips (Jul. 2015)
- Nvidia cancels Shield tablet (Aug. 2016)
- ARM acquired by Softbank (Sep. 2016)
- Apple tells Imagination that their IP will not be needed in 18-24 months (Apr. 2017)

Architectures (nowadays)



Acquired by Imagination, inc



Architectures – ARM

- **ARM Ltd.**
 - RISC processor (32/64 bit)
 - IP (intellectual property) – Instruction Set / ref. implementation
 - CPU / GPU (Mali)
- **Licenses (instruction set OR ref. design)**
 - **Instruction Set** license -> custom made design (SnapDragon, Samsung in Galaxys, Apple in iPones & iPads)
 - Optimizations (particular paths, improved core freq. control,...)
 - **Reference design** (Cortex A9, Cortex A15, Cortex A53/A57...)
- **Licensees (instruction set OR ref. design)**
 - Apple, Qualcomm, Samsung, Nvidia, AMD, MediaTek, Amazon (through Annapurna Labs, Inc.)...
 - Few IS licenses, mostly adopting reference design
- **Manufacturers**
 - Contracted by Licensees
 - GlobalFoundries, United Microelectronics, TSM...

Architectures – ARM...

- **Supported on**
 - Android, iOS, Win Phone, Tizen, Firefox OS, BlackBerry, Ubuntu Phone, ...
- **Biggest mobile market share**
- **Typically paired with mobile GPUs. Existing brands:**
 - Adreno 4x0/5x0 – Qualcomm
 - PowerVR 8XE (Rogue) – Imagination
 - Mali T8x0/G51/G71 – ARM
- **General strategies:**
 - Cache coherence – weak sequential code guarantees on multithreading!!
 - Heavy **dependence on compiler** → optimize instruction scheduling
 - Operation dependencies , loop unrolling, etc...
 - Use SIMD extensions

Architecture types

- **High performance**
 - Premium smartphones & tablets
- **High area efficiency**
 - Medium-to-low smartphones
- **Ultra-low power**
 - Smartwatches

Architectures

Mobile GPU architecture trends

Graphics pipeline trends

- **Tiled rendering**
- **Data (texture) compression**
- **Other optimizations**

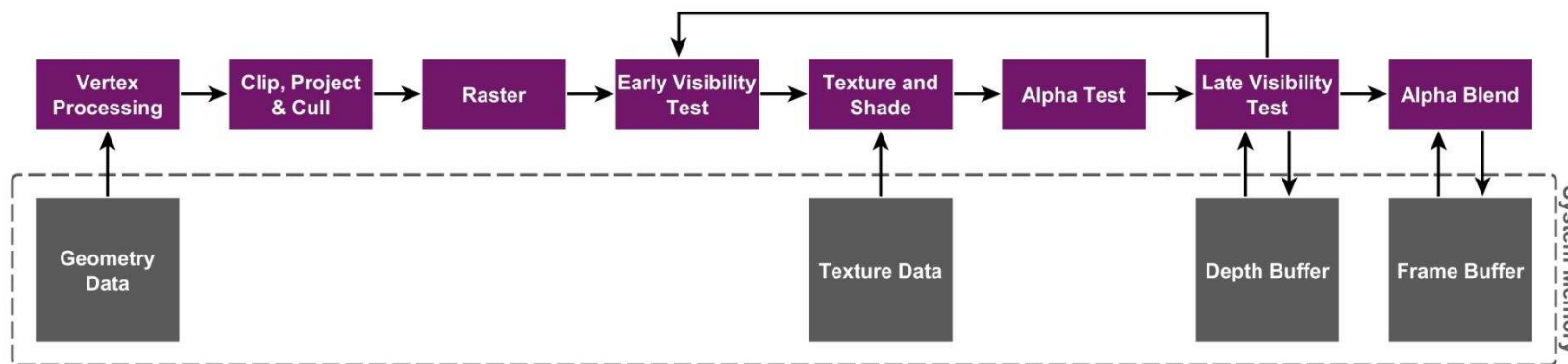
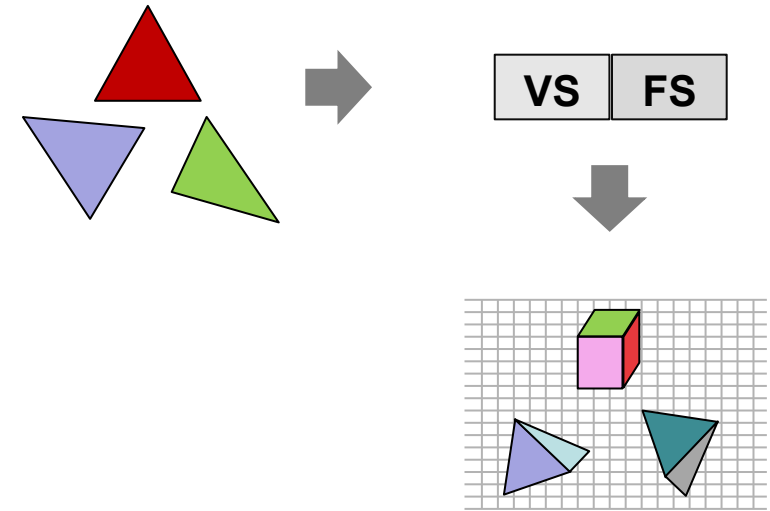
Tiled Rendering

- Immediate Mode Rendering (IMR)
- Tile-Based Rendering (TBR)
- Tile-Based Deferred Rendering (TBDR)

Architectures – GPU

• Immediate Mode Rendering (IMR)

- Geometry is processed in submission order
 - High **overdraw** (shaded pixels can be overwritten)
- Buffers are kept in System Memory
 - High bandwidth / power / latency
- Early-Z helps depending on geometry sorting
 - Depth buffer value closer than fragment → discard

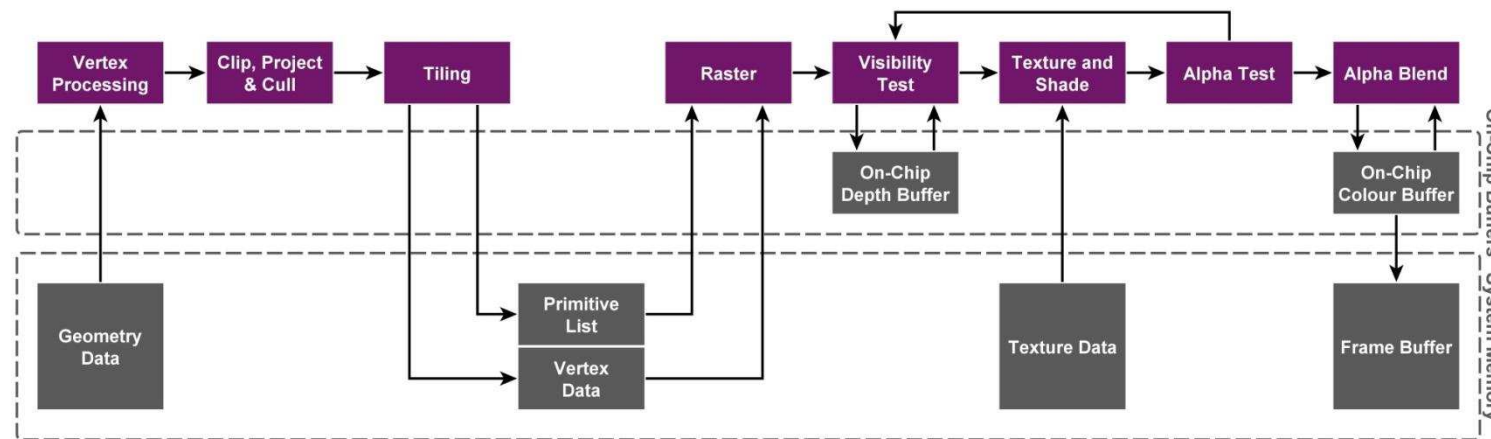
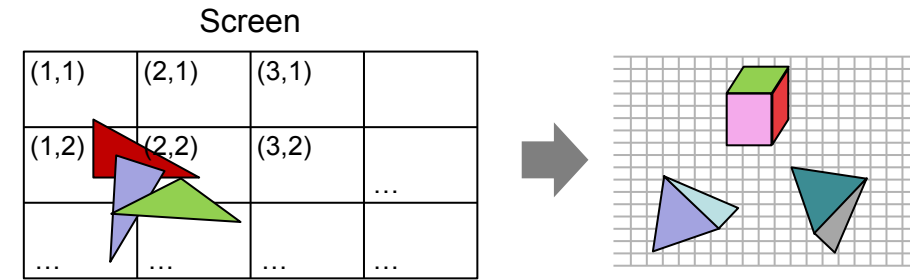


<http://blog.imgtec.com/powervr/understanding-powervr-series5xt-powervr-tbdr-and-architecture-efficiency-part-4>

Architectures – GPU

• Tile Based Rendering (TBR)

- Rasterizing per-tile (triangles in bins per tile) 16x16, 32x32
 - Buffers are kept on-chip memory (GPU) – fast! → **geometry limit?**
- Triangles processed in submission order (TB-IMR)
 - **Overdraw (front-to-back -> early z cull)**
- Early-Z helps depending on geometry sorting

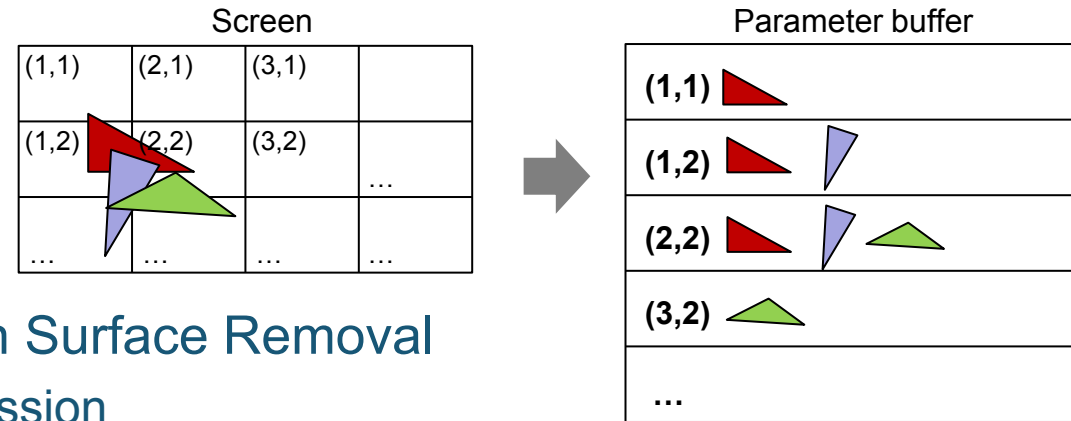


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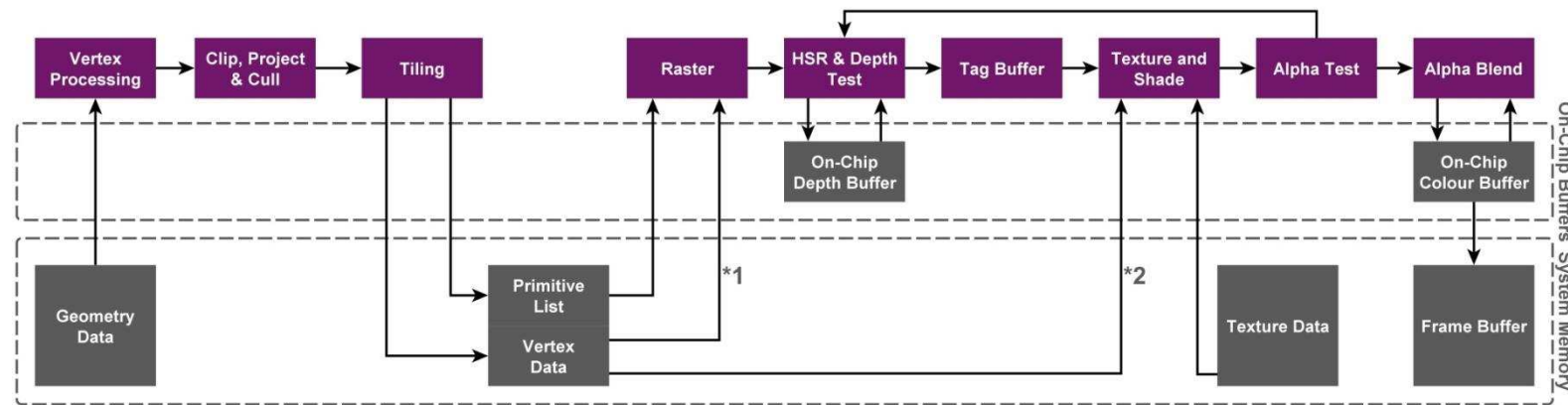
Architectures – GPU

• Tile Based Deferred Rendering (TBDR)

- Fragment processing (tex + shade) ~waits for Hidden Surface Removal
 - Micro Depth Buffer – depth test before fragment submission
 - whole tile → **1 frag/pixel** 😊
 - iPAD 2X slower than Desktop GeForce at HSR (FastMobileShaders_siggraph2011)
- Possible to prefetch textures before shading/texturing
- Hard to profile!!! ~~~Timing?



Limit: ~100Ktri + complex shader



<http://blog.imgtec.com/powervr/understanding-powervr-series5xt-powervr-tbdr-and-architecture-efficiency-part-4>

Data/texture compression

- ARM's Adaptive Scalable Texture Compression (ASTC) supported by most mobile GPU vendors
- ETC2/EAC standard compression OpenGL ES 3.0
- Compression hardware also present in display hardware
 - Rendered images stored and transferred to the display in a compressed
 - Saving bandwidth

Other optimizations

- Deferred shading
- Primitive elimination
- Skipping updates to pixels that do not change
 - ARM memory transaction elimination

Trends

- Specific hardware for ray tracing
- Learning libraries & hardware (e.g. Qualcomm's Fast CV, Nvidia's CUDA Deep Neural Network)
- Skipping updates to pixels that do not change
 - ARM memory transaction elimination

Part 2.2

Mobile Graphics Trends: Applications

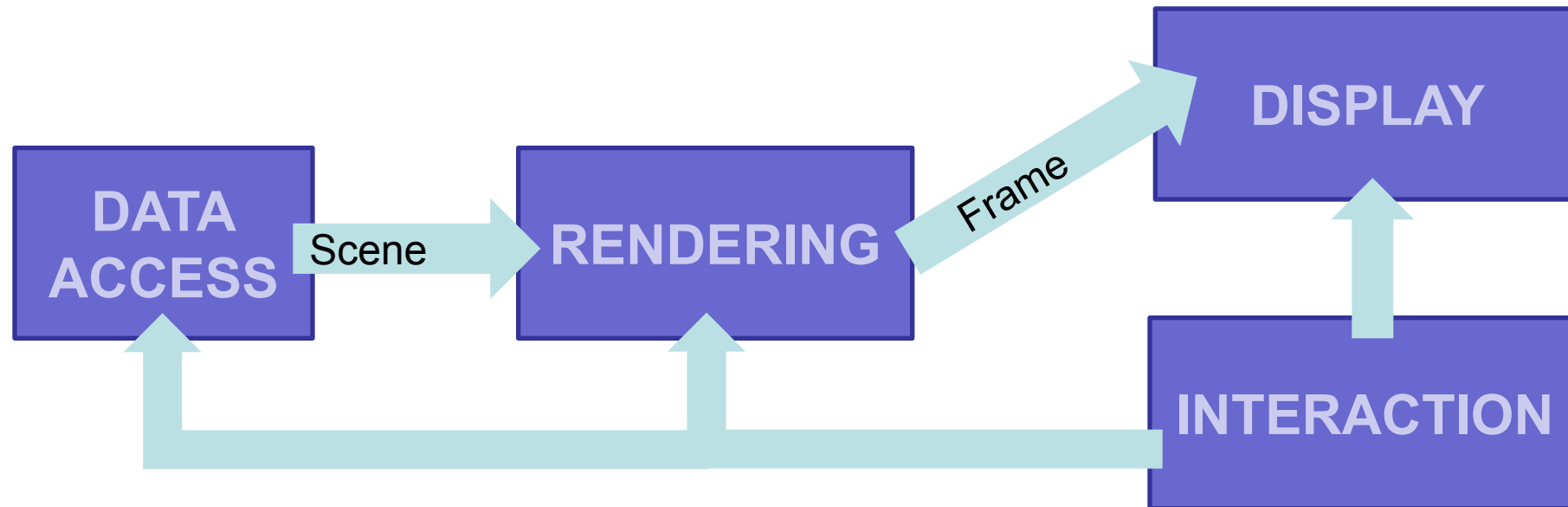
Marco Agus, KAUST & CRS4

Applications

- **Wide range of applications**
 - Cultural Heritage
 - Medical Image
 - 3D object registration
 - GIS
 - Gaming
 - VR & AR
 - Building reconstruction
 - Virtual HCI

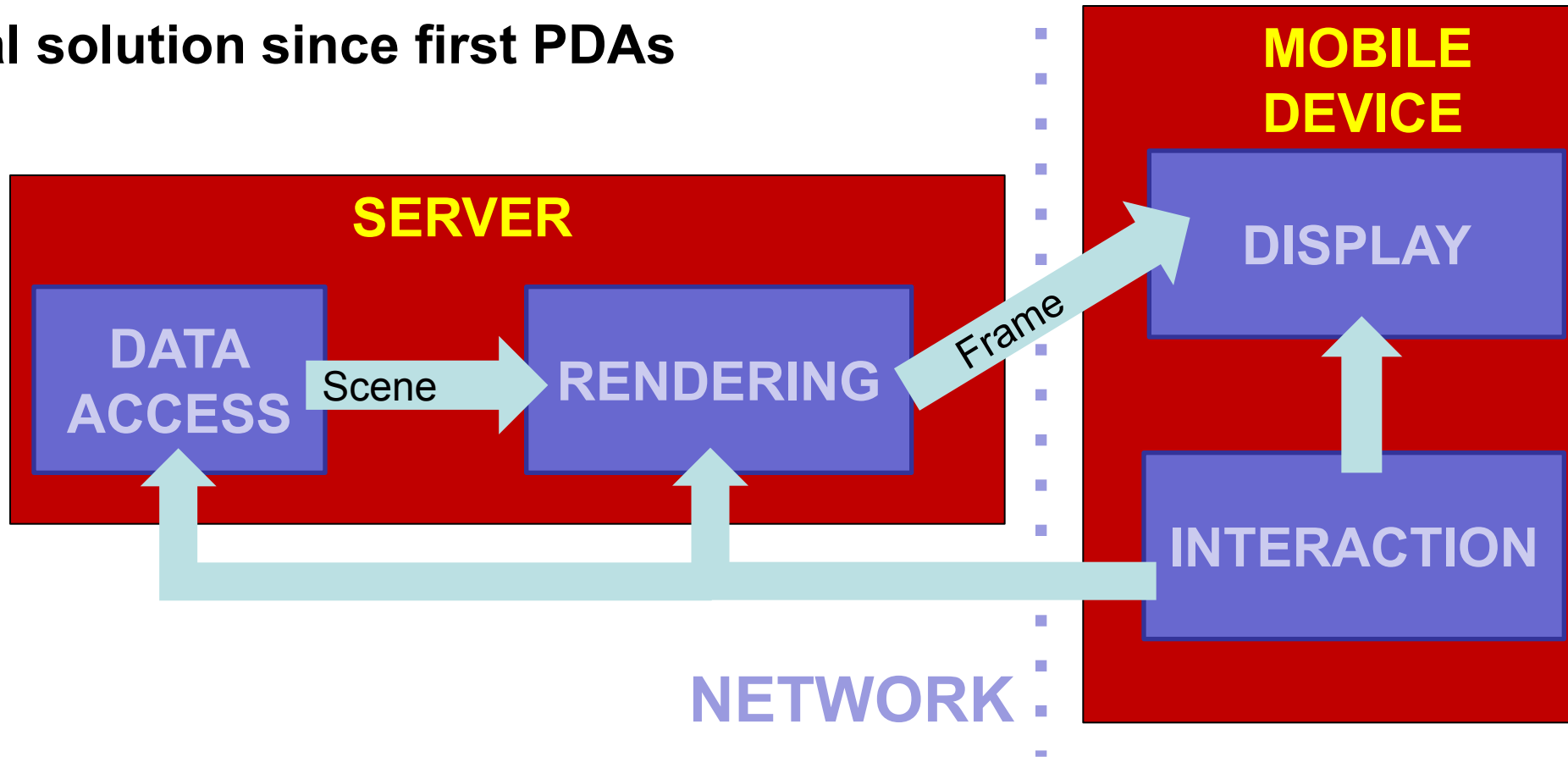
Mobile 3D interactive graphics

- General pipeline similar to standard interactive applications



Remote rendering

- General solution since first PDAs

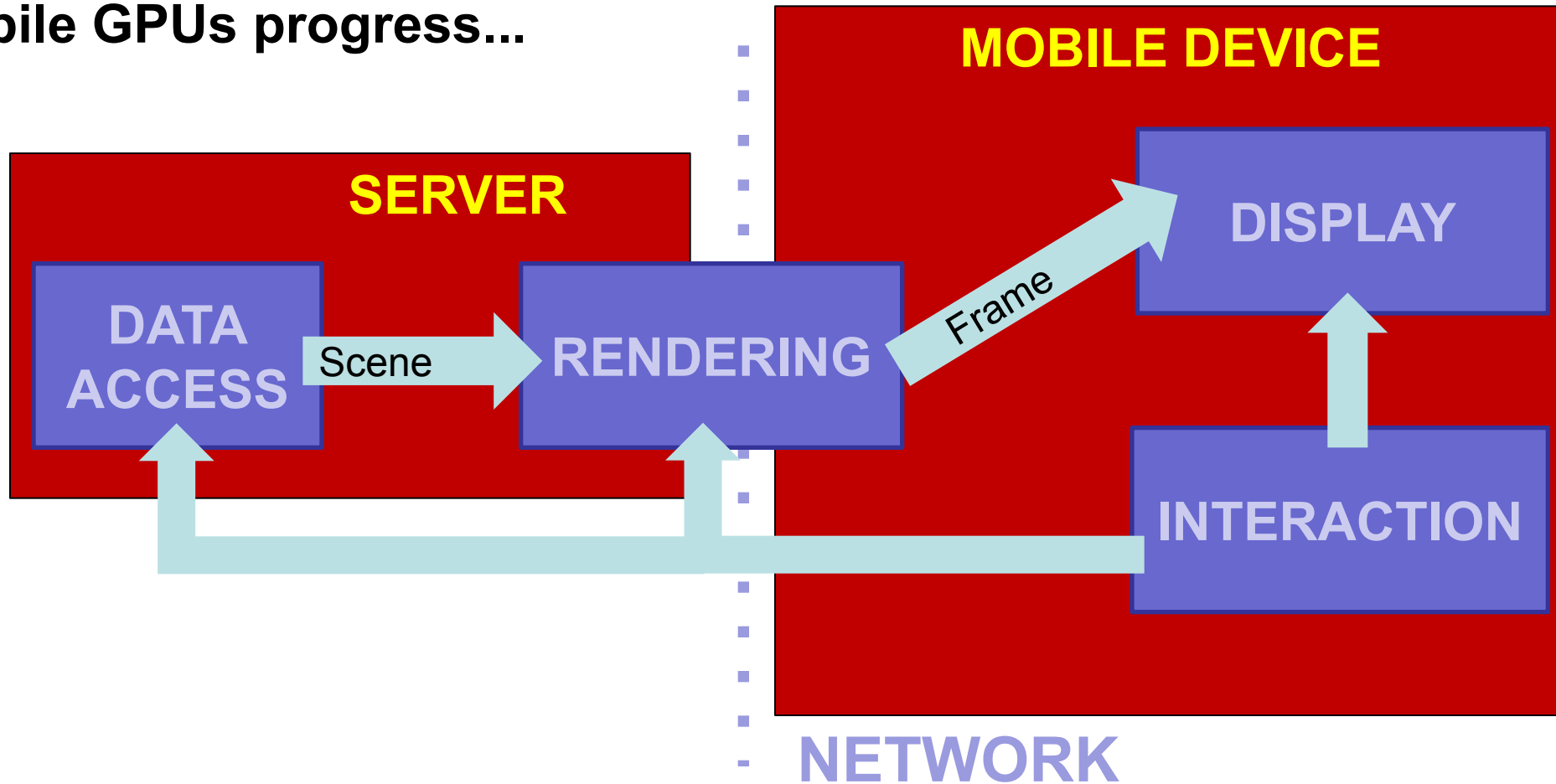


Remote rendering

- **3D graphics applications require intensive computation and network bandwidth**
 - electronic games
 - visualization of very complex 3D scenes
- **Remote rendering has long history and it is successfully applied for gaming services**
 - Limitation: interaction latency in cellular networks

Mixed Mobile/Remote rendering

- As mobile GPUs progress...



Mixed Mobile/Remote rendering

- **Model based versus Image based methods**
- **Model based methods**

- Original models

Eisert and Fechteler. **Low delay streaming of computer graphics** (ICIP 2008)

- Partial models

Gobbetti et al. **Adaptive Quad Patches: an Adaptive Regular Structure for Web Distribution and Adaptive Rendering of 3D Models.** (Web3D 2012)

Balsa et al.,. **Compression-domain Seamless Multiresolution Visualization of Gigantic Meshes on Mobile Devices** (Web3D 2013)

- Simplified models

- Couple of lines

Diepstraten et al., 2004. **Remote Line Rendering for Mobile Devices** (CGI 2004)

- Point clouds

Duguet and Drettakis. **Flexible point-based rendering on mobile devices** (IEEE Trans. on CG & Appl, 2004)

Mixed Mobile/Remote rendering

- Model based versus Image based methods
- Model based methods

Point clouds
organized as
hierarchical grids.
Tested on PDAs



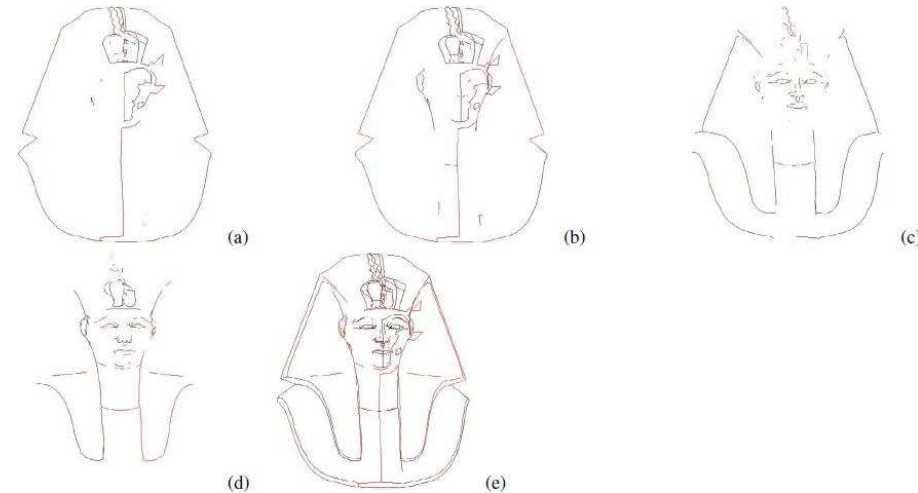
- Point clouds

Duguet and Drettakis. **Flexible point-based rendering on mobile devices** (IEEE Trans. on CG & Appl, 2004)

Mixed Mobile/Remote rendering

- Model based versus Image based methods
- Model based methods

Transfer couple of 2D line primitives over the network, which are rendered locally by the mobile device



- Couple of lines



Diepstraten et al., 2004. **Remote Line Rendering for Mobile Devices** (CGI 2004)

- Point clouds

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Mixed Mobile/Remote rendering

- Model based versus Image based methods
- Model based methods
 - Original models



Eisert and Fechteler. **Low delay streaming of computer graphics** (ICIP 2008)



Intercept and stream OpenGL commands
 Better performances with respect to video streaming
Limitation: clients need powerful GPU

Mixed Mobile/Remote rendering

- **Model based versus Image based methods**
- **Model based methods**

- Original models

Eisert and Fechteler. **Low delay streaming of computer graphics** (ICIP 2008)

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- Simplified models

- Couple of

Mobile

More details in Part 4

- Point cloud

g on

mobile devices (IEEE Trans. on CG & Appl, 2004)

Mixed Mobile/Remote rendering

- **Image based methods**

- **Image impostors**

Noimark and Cohen-Or. **Streaming scenes to mpeg-4 video-enabled devices** (IEEE, CG&A 2003)

Lamberti and Sanna. **A streaming-based solution for remote visualization of 3D graphics on mobile devices** (IEEE, Trans. VCG, 2007)

- **Environment maps**

Bouquerche and Pazzi. **Remote rendering and streaming of progressive panoramas for mobile devices** (ACM Multimedia 2006)

- **Depth images**

Zhu et al. **Towards peer-assisted rendering in networked virtual environments** (ACM Multimedia 2011)

Shi et al. **A Real-Time Remote Rendering System for Interactive Mobile Graphics** (ACM Trans. On Multimedia, 2012)

Doellner et al. **Server-based rendering of large 3D scenes for mobile devices using G-buffer cube maps** (ACM Web3D, 2012)

Mixed Mobile/Remote rendering

- **Image based methods**

- Image impostors

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- Enviro

Bouquet
for mob

Image representations are created by the server,
and warped in real time by the client to account for
user interaction

mas

- Depth

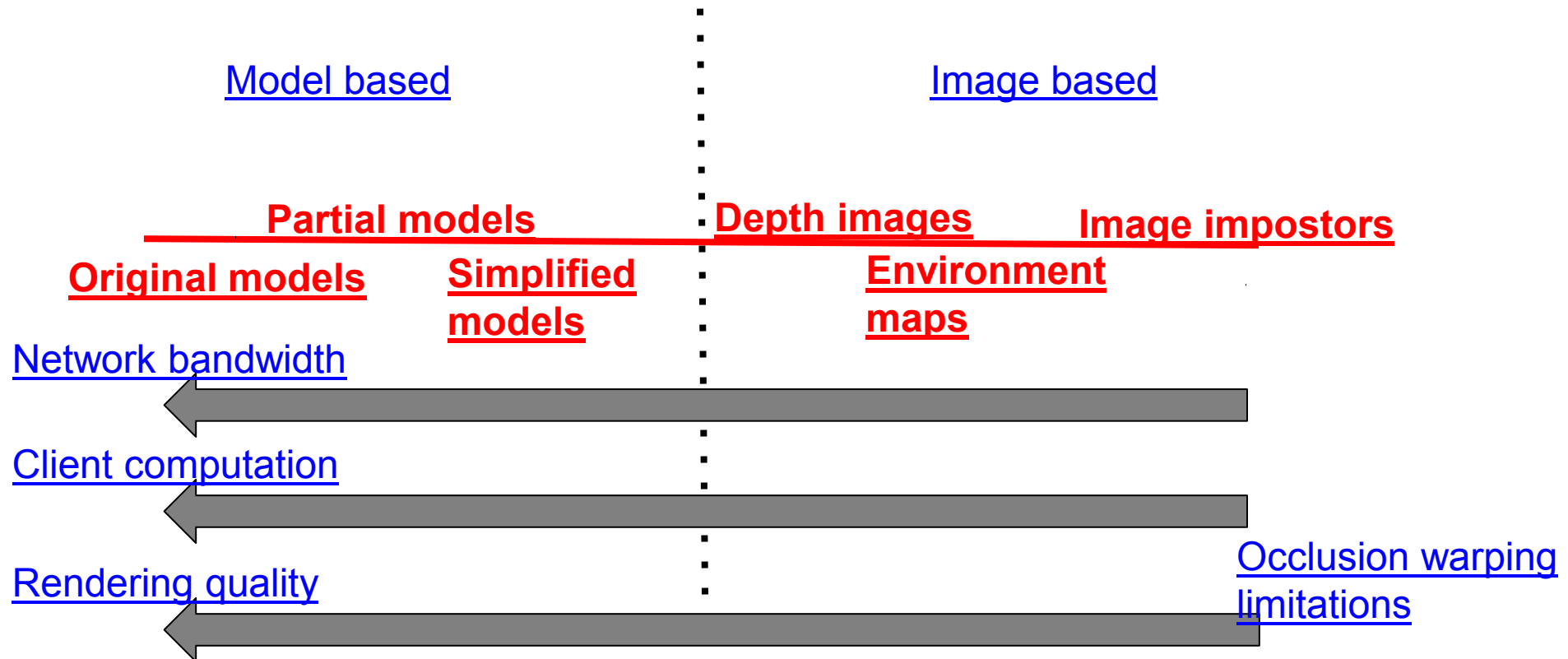
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Mixed Mobile/Remote rendering

- **Model based vs Image based methods**
 - Constraints: rendering quality, bandwidth, interactivity



Mobile visualization systems

- **Volume rendering**

Moser and Weiskopf. **Interactive volume rendering on mobile devices**. Vision, Modeling, and Visualization VMV. Vol. 8. 2008.

Noguerat al. **Volume Rendering Strategies on Mobile Devices**. GRAPP/IVAPP. 2012.

Campoalegre, Brunet, and Navazo. **Interactive visualization of medical volume models in mobile devices**. Personal and ubiquitous computing 17.7 (2013): 1503-1514.

Rodríguez, Marcos Balsa, and Pere Pau Vázquez Alcocer. **Practical Volume Rendering in Mobile Devices**. Advances in Visual Computing. Springer, 2012. 708-718.

- **Point cloud rendering**

Balsa et al. **Interactive exploration of gigantic point clouds on mobile devices**. (VAST 2012)

He et al. **A multiresolution object space point-based rendering approach for mobile devices** (AFRIGRAPH, 2007)

Mobile visualization systems

- **Volume rendering**

Moser and Weiskopf. **Interactive volume rendering on mobile devices**. Vision, Modeling, and Visualization VMV. Vol. 8. 2008.

Noguerat al. **Volume Rendering Strategies on Mobile Devices**. GRAPP/IVAPP. 2012.

see section 4 for details

Campoalegre **Visualization of medical volume models in mobile devices**. Personal and ubiquitous computing 17.7 (2013): 1503-1514.

→ Rodríguez, Marcos Balsa, and Pere Pau Vázquez Alcocer. **Practical Volume Rendering in Mobile Devices**. Advances in Visual Computing. Springer, 2012. 708-718.

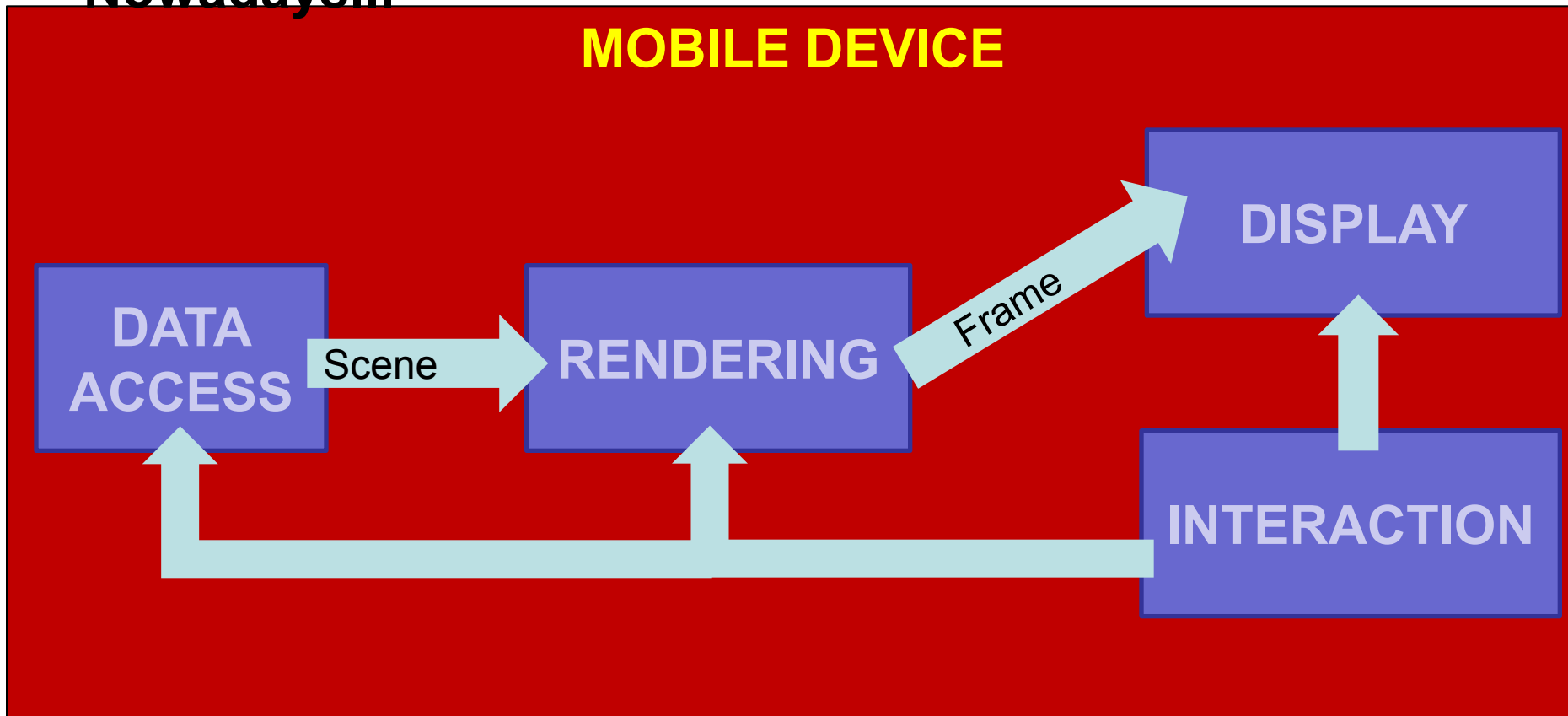
- **Point cloud rendering**

→ Balsa et al. **Interactive exploration of gigantic point clouds on mobile devices**. (VAST 2012)

He et al. **A multiresolution object space point-based rendering approach for mobile devices** (AFRIGRAPH, 2007)

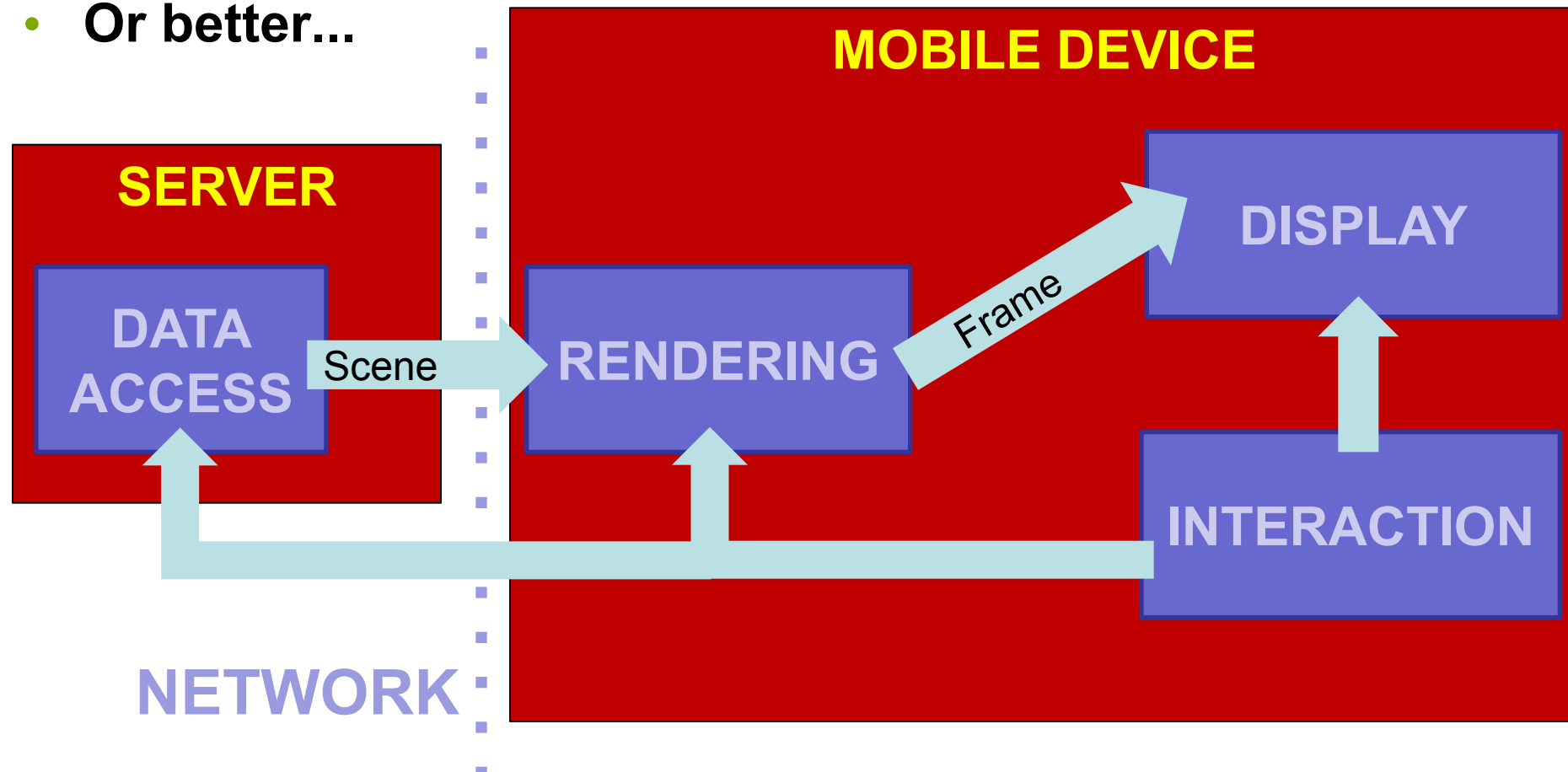
Mobile rendering

- Nowadays...



Mobile rendering

- Or better...



Mobile rendering

- Or better...

SERVER

Chunk-based data streaming
(like HuMoRS Balsa et al. 2014)

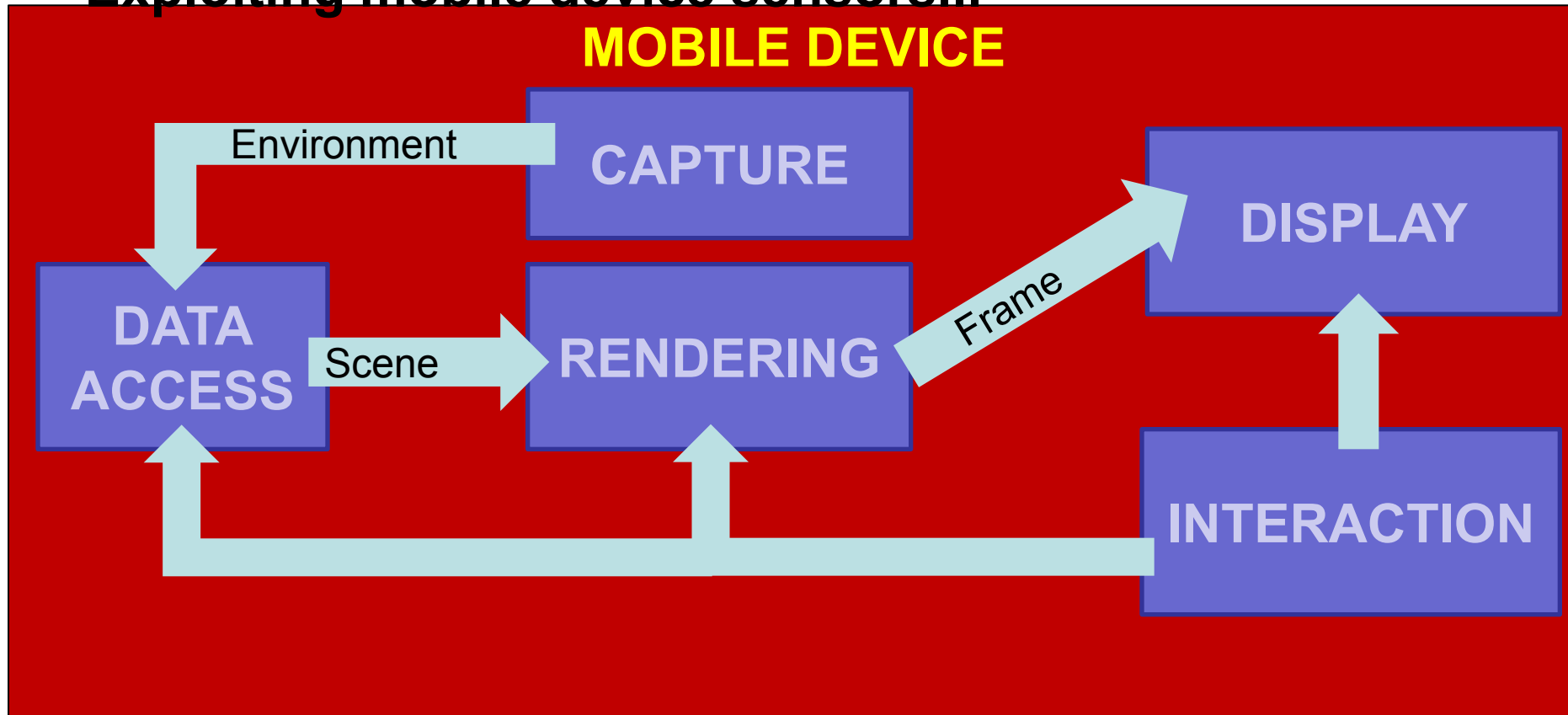
Limitations: bandwidth consumption (for now)

NETWORK



Mobile rendering with capture

- Exploiting mobile device sensors...



Mobile rendering with capture


- Exploiting mobile device sensors...

MOBILE DEVICE

Environment

CAP

3D scanning with mobile phone
Kolev et al, CVPR 2014
ETH Zurich

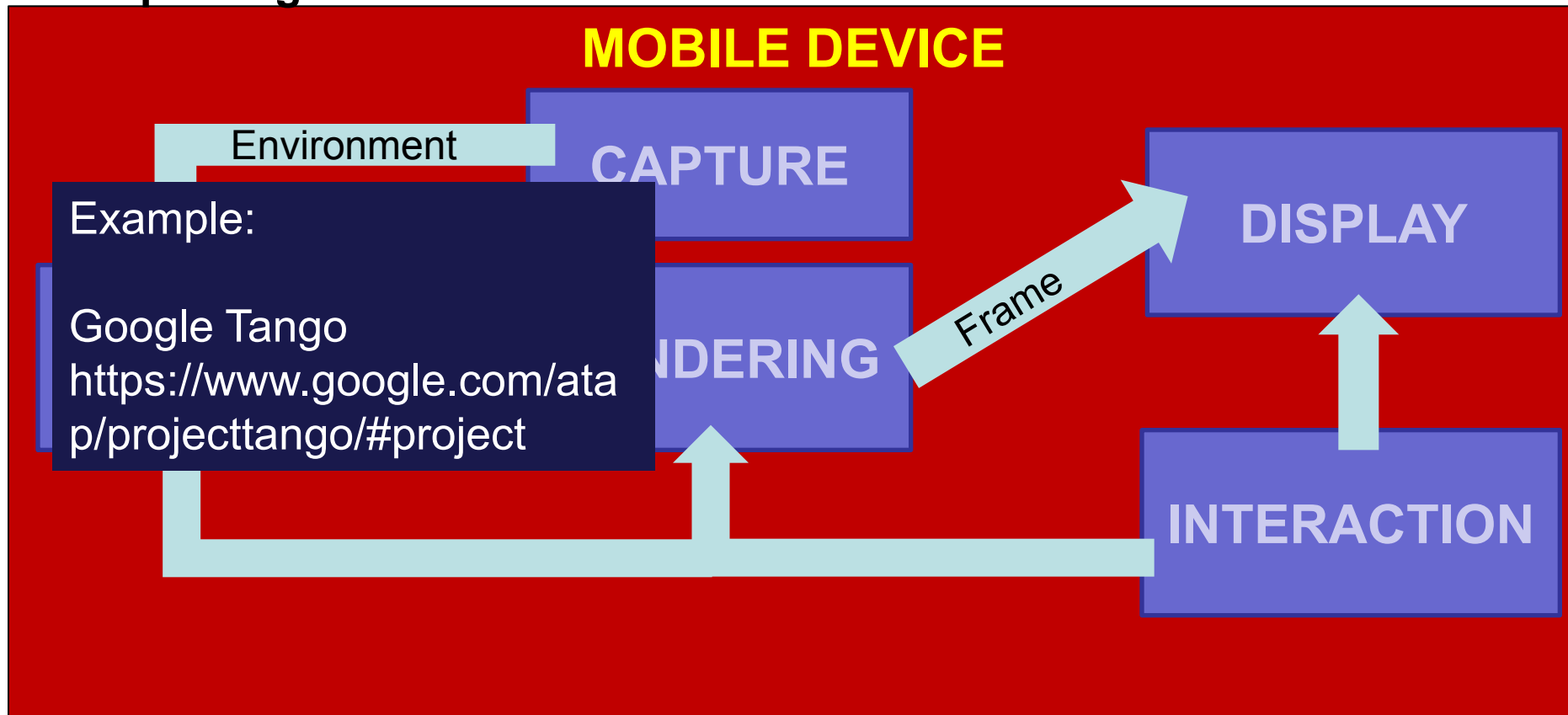


Kolev et al. **Turning Mobile Phones into 3D Scanners** (CVPR 2014)

Tanskanen et al. **Live Metric 3D Reconstruction on Mobile Phones** (ICCV 2013)

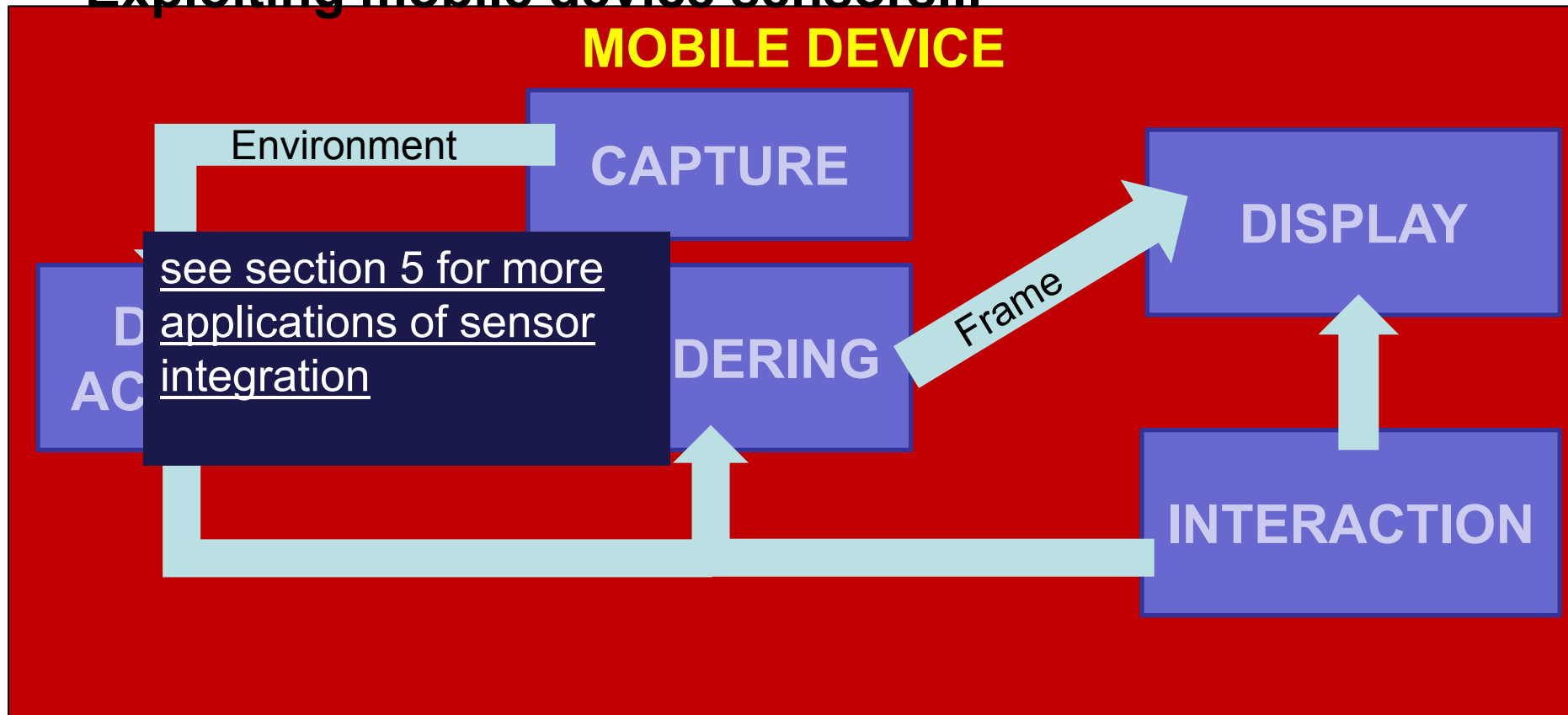
Mobile rendering with capture

- Exploiting mobile device sensors...



Mobile rendering with capture

- Exploiting mobile device sensors...



Trends in mobile graphics

- **Hardware acceleration for improving frame rates, resolutions and rendering quality**
 - Parallel pipelines
 - Real-time ray tracing
 - Multi-rate approaches

SGRT: Real-time ray tracing

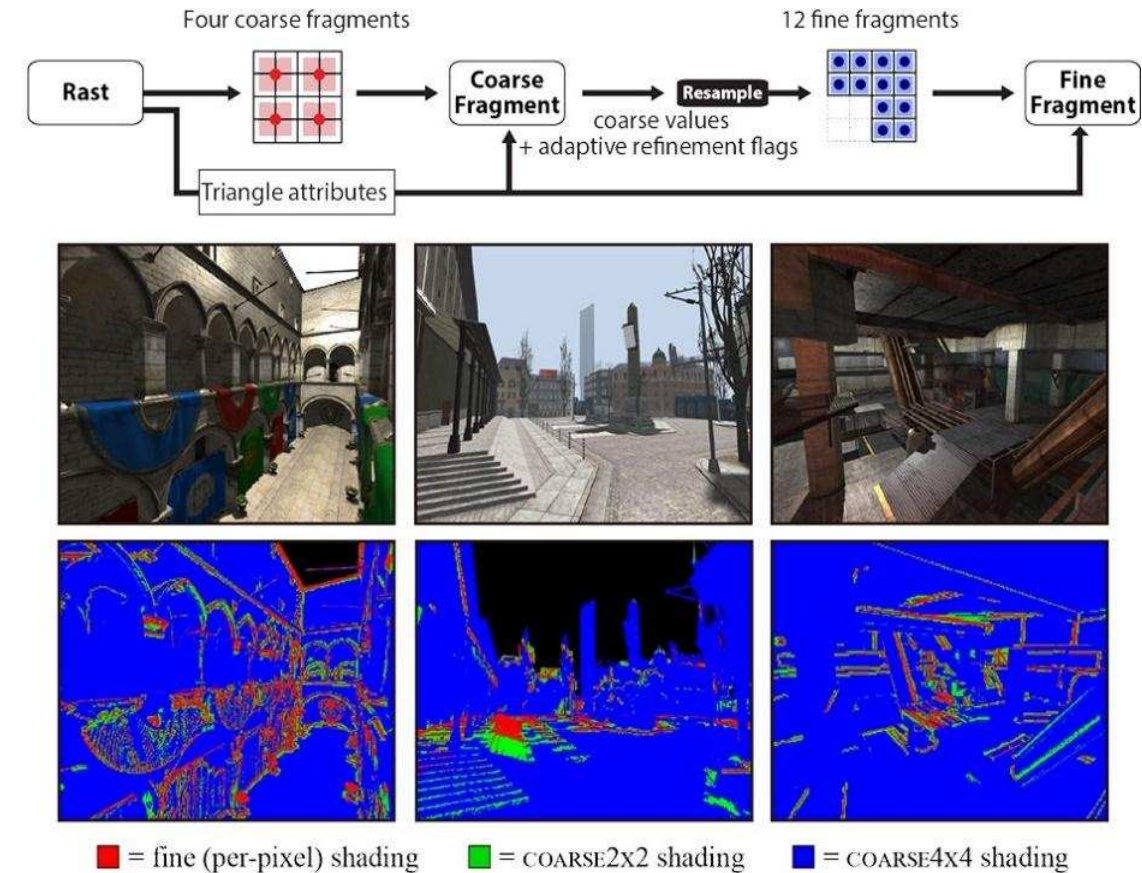
- **Samsung reconfigurable GPU based on Ray Tracing**
- **Main key features:**
 - an area-efficient parallel pipelined traversal unit
 - flexible and high-performance kernels for shading and ray generation

Shin et al., **Full-stream architecture for ray tracing with efficient data transmission**, 2014 IEEE ISCAS

Lee, Won-Jong, et al. **SGRT: A mobile GPU architecture for real-time ray tracing**. Proceedings of the 5th High-Performance Graphics Conference, 2013.

Adaptive shading

- Triangles rasterized into coarse fragments that correspond to multiple pixels of coverage
- Coarse fragments are shaded, then partitioned into fine fragments for subsequent per-pixel shading



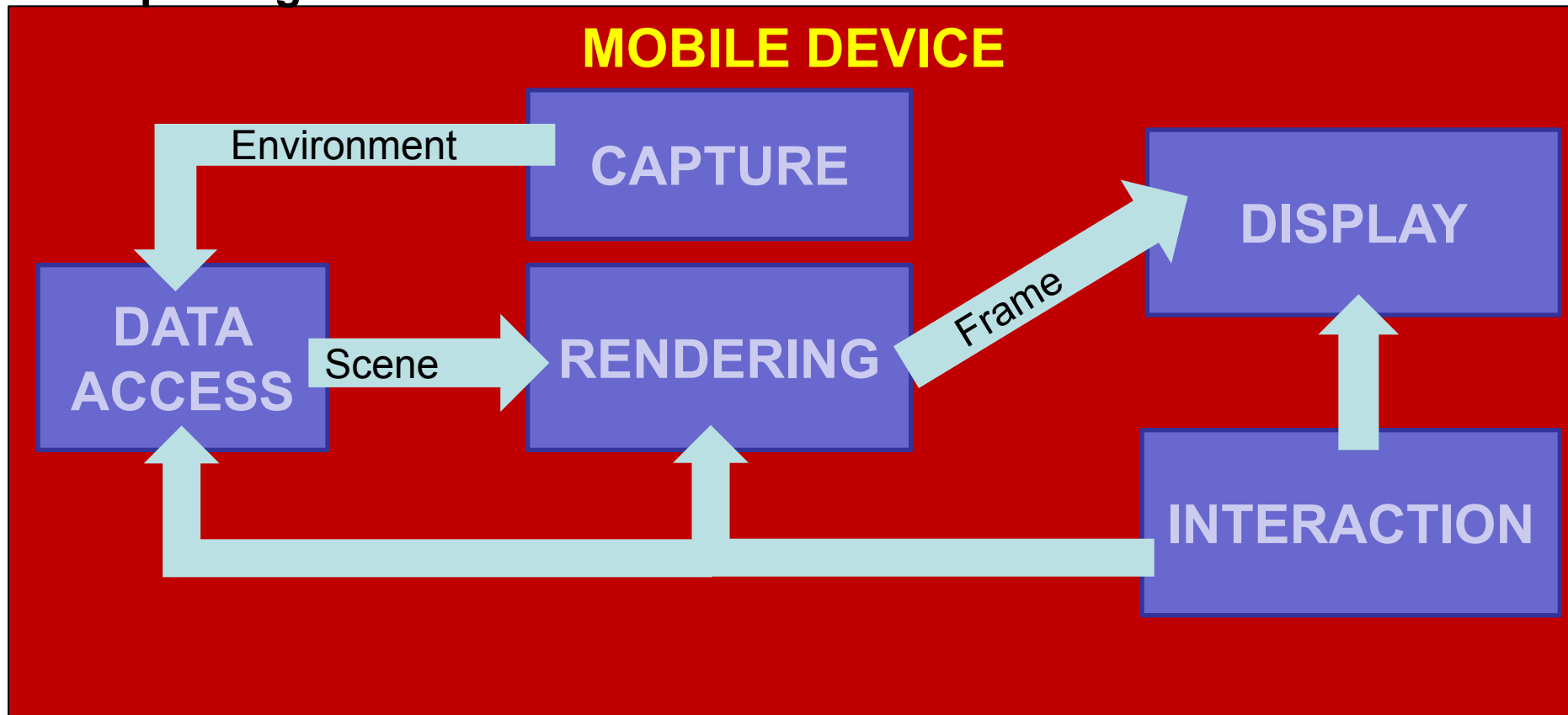
He et al. **Extending the graphics pipeline with adaptive, multi-rate shading.** ACM Transactions on Graphics (TOG) 33.4 , 2014.

Clarberg, Petrik, et al. **AMFS: adaptive multi-frequency shading for future graphics processors.** ACM Transactions on Graphics (TOG) 33.4 , 2014.

Won-Jong Lee, et al. **Adaptive multi-rate ray sampling on mobile ray tracing GPU.** In SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications (SA '16).

Mobile rendering with capture

- Exploiting mobile device sensors...



Examples: Physical simulations

- Framework for physically and chemically-based simulations of analog alternative photographic processes
- Efficient fluid simulation and manual process running on iPad



Echevarria et al. **Computational simulation of alternative photographic processes**. Computer Graphics Forum. Vol. 32. 2013.

Examples: Correcting visual aberrations

- Computational display technology that predistorts the presented content for an observer, so that the target image is perceived without the need for eyewear
- Demonstrated in low-cost prototype mobile devices



Huang, Fu-Chung, et al. **Eyeglasses-free display: towards correcting visual aberrations with computational light field displays**. ACM Transactions on Graphics (TOG) 33.4, 2014.

Conclusions

- **Heterogeneous applications**
 - driven by bandwidth and processing power
- **Trends**
 - desktop software solutions tend to be ported to the mobile world
 - gaming
 - modelling and 3D animation
 - complex illumination models
- **Sensor integration open new scenarios**
 - examples: live acquisition, mHealth (using sensors and cameras for tracking and processing signals)

•

Next Session

GRAPHICS DEVELOPMENT FOR MOBILE SYSTEMS

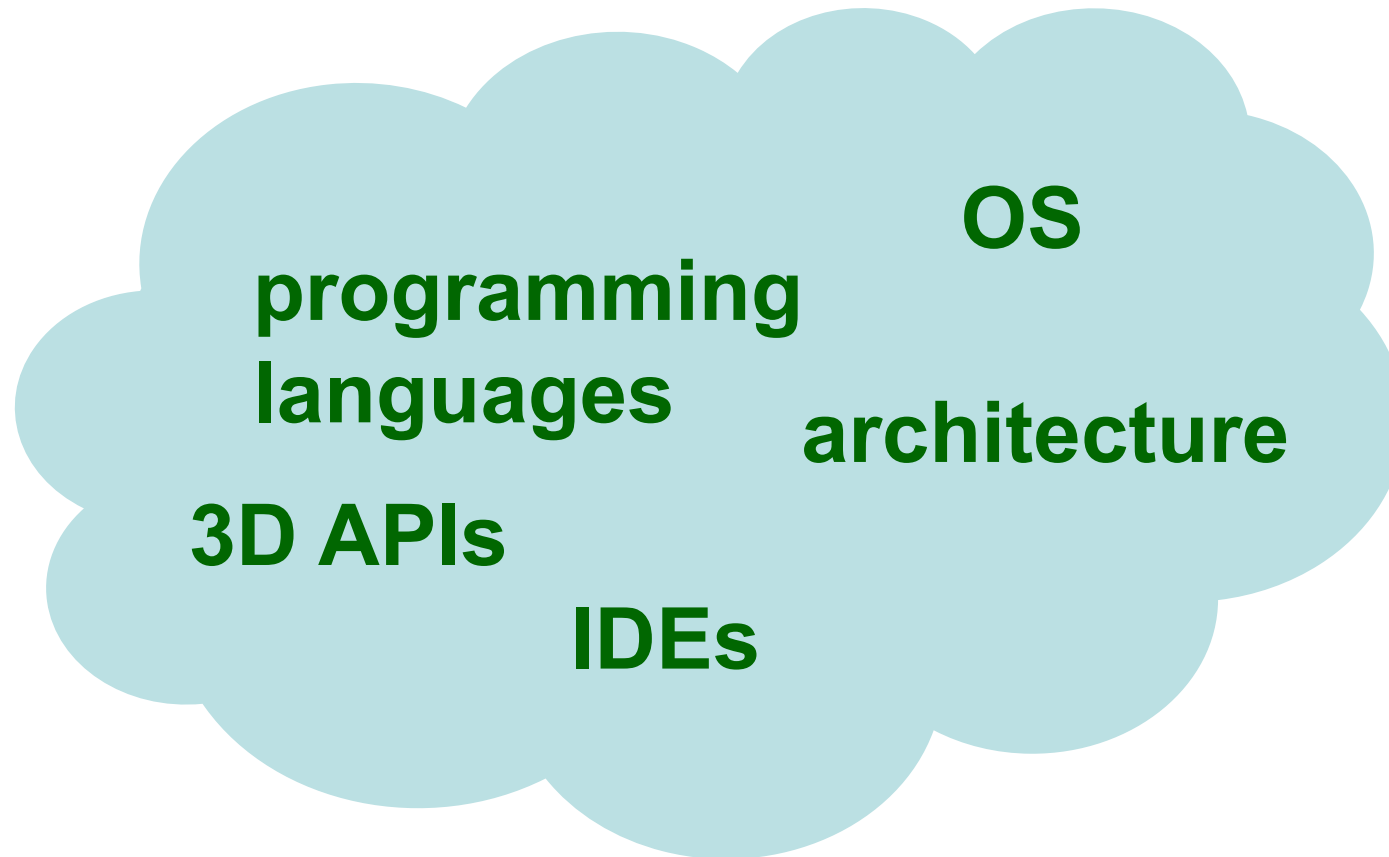
Part 3

Graphics development for mobile systems

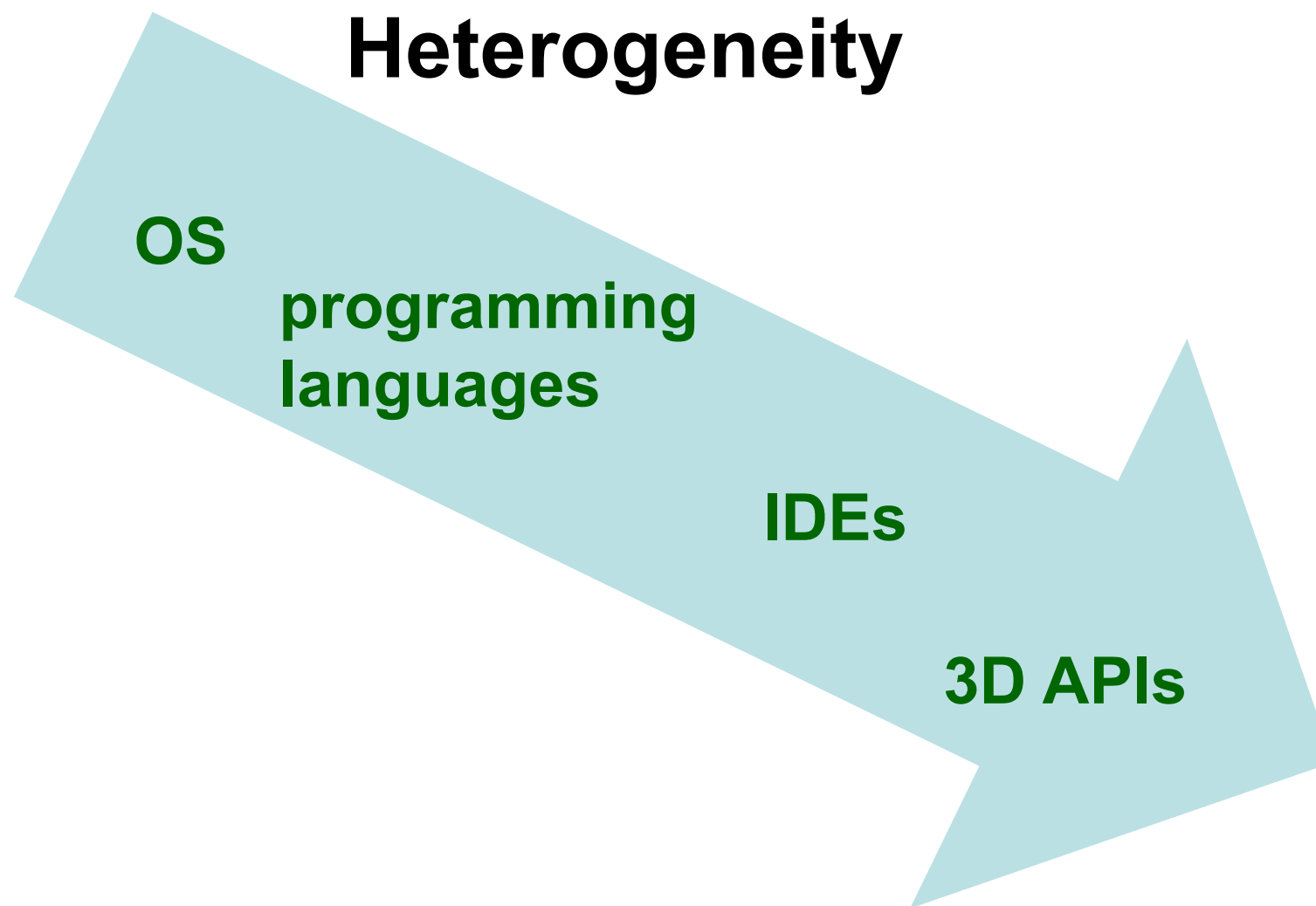
Marco Agus, KAUST & CRS4

Mobile Graphics

Heterogeneity



Mobile Graphics



Mobile Graphics

- **OS**
 - Android
 - iOS
 - Windows Phone
 - Firefox OS, Ubuntu Phone, Tizen...
- **Programming Languages**
 - C++
 - Obj-C / Swift
 - Java
 - C# / Silverlight
 - HTML5/JS/CSS
- **Architectures**
 - X86 (x86_64): Intel / AMD
 - ARM (32/64bit): ARM + (Qualcomm, Samsung, Apple, NVIDIA,...)
 - MIPS (32/64 bit): Ingenics, Imagination.
- **3D APIs**
 - OpenGL / GL ES
 - D3D / ANGLE
 - Metal / Mantle / Vulkan (GL Next)
- **Cross-development**
 - Qt
 - Marmalade / Xamarin /
 - Muio
 - Monogame / Shiva3D / Unity / UDK4 / Cocos2d-x

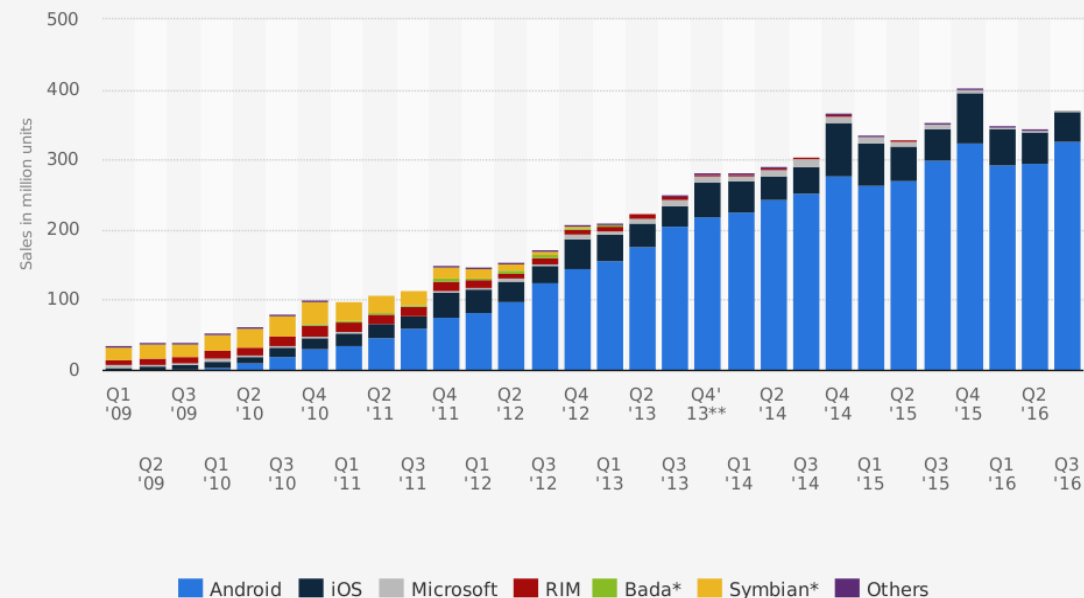
Operating Systems



Operating Systems

- **Linux based (Qt...)**
 - Ubuntu, Tizen, BBOS...
- **Web based (Cloud OS)**
 - ChromeOS, FirefoxOS, WebOS
- **Windows Phone**
- **iOS (~unix + COCOA)**
- **Android (JAVA VM)**

Global smartphone sales to end users from 1st quarter 2009 to 3rd quarter 2016, by operating system (in million units)



Source:
Gartner
© Statista 2016

Additional Information:
Worldwide; Gartner; 1st quarter 2009 to 3rd quarter 2016

statista

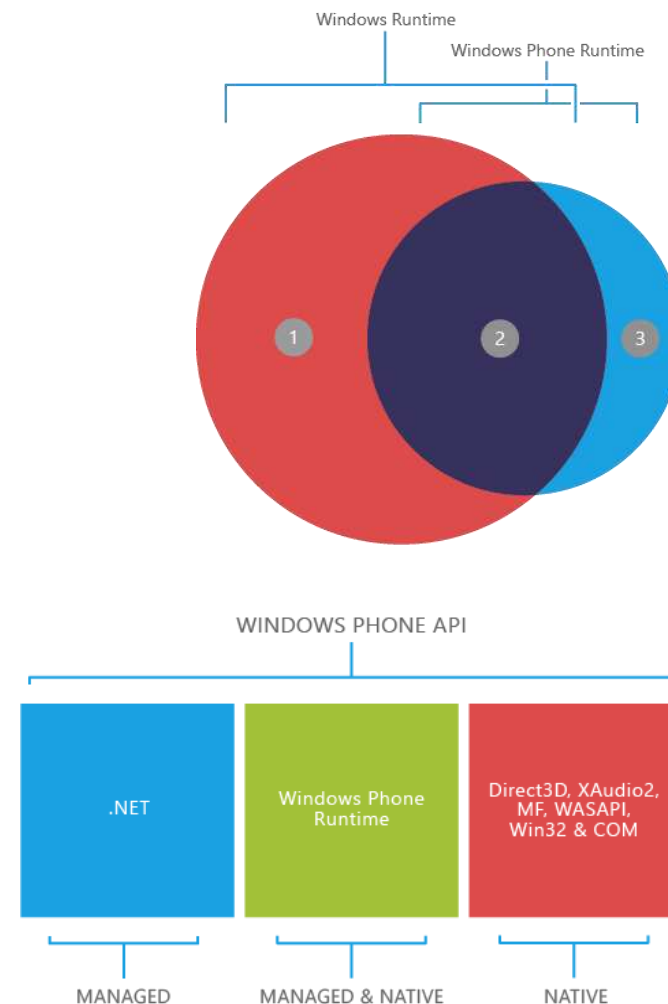
Development trends

- **Hard to follow the trends**
 - software does not follow hardware evolution
 - strong market oriented field where finance has strong impact on evolution
- **In general, for**
 - Mobile phones
 - Market drive towards Android, iOS
 - Tablets
 - Android, iOS, Windows 10
 - Embedded devices
 - Heterogenous (beyond the scopes of this course)
- **Here we focus on mobile phones and tablets**

Operating Systems

Windows 10

- Windows development – Visual Studio 2017
 - Good debugging / compiler / integration
- Great integration and deployment
 - Universal Windows Platform (UWP)
- API access
 - C#, VB.NET, and C++
- 3D API
 - D3D
 - OpenGL access through ANGLE
- Advantages
 - **Visual Studio, interoperability with iOS**
 - **HW is quite selected/homogeneous**
- Disadvantages
 - **~OpenGL wrapper just recently!**



Operating Systems

- **iOS**
 - Development under MacOS
 - Xcode – good IDE/debug
 - **Clang** compiler!
 - API access
 - Objective-C, **swift**
 - Library programming
 - C++ support
 - Advantages:
 - **Homogeneous hardware** (biggest issues are resolution related)
 - **State-of-the-art CPU/GPU** (PowerVR SGX 54X/554, G6400)
 - **Good dev tools** (Xcode + Clang)
 - Inconvenients:
 - **Closed platform**
 - Requires **iDevice** for development/shipment (mostly)

Operating Systems

- **Android**
 - Development in Eclipse / AndroidStudio
 - Java-based – integrated debugging (non-trivial for NDK)
 - GCC / clang compilers
 - Advantages
 - Wide **variety** of hardware configurations (CPU/GPU)
 - Java based + C++ as dynamic library (JNI or NDK+NativeActivity)
 - Open source
 - Toolchain provided for Windows/Linux/macOS (GCC + Clang)
 - Faster **access** to new hardware / functionality!
 - Inconvenients
 - **Heterogeneous** device base (hard to target all configurations)
 - **Not so integrated** IDE -- ~mixed pieces

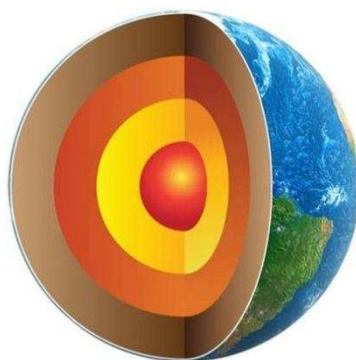
Operating Systems (comparison)

- **App development -- publishing**
 - WinPhone & iOS requires less effort for distribution
 - Easy to reach the whole user base
 - Android has a wide variety of configuration that require tuning
 - User base is typically reached in an incremental way (supporting more configs)
 - Many HW configurations (CPU/GPU) give more options to explore 😊
 - Windows has not yet the same market share
 - Variety of configurations

Programming Languages

- **C/C++**
 - Classic, performance, codebase, control
- **Objective C**
 - Bit different style (message based), well-documented API for iOS, mainly COCOA/iOS
- **Java**
 - Android is VM/JIT based, ~portability (API), well-known, extended, codebase
- **C#**
 - VM based, ~Java evolution, (Win, Android, iOS)
- **Swift**
 - Apple new language, simplicity, performance, easy, LLVM-based compilers
- **HTML5/JS**
 - Web technologies, extended, compatibility
- **Perl, Python, Ruby, D, GO (Google), Hack (facebook), ...**
 - More options, not so popular ?

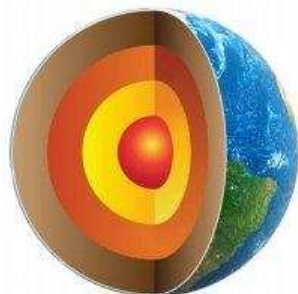
3D APIs



3D APIs

Cross Platform Challenge

- An explicit API that is also cross-platform needs careful design



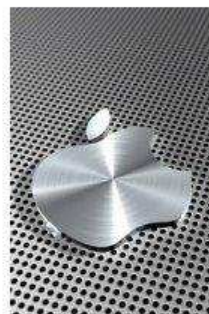
One family
of GPUs

Mantle



One OS

Direct3D



One GPU on
one OS

Metal



**OpenGL Next
5.0**

Khronos
GROUP

3D APIs

- **Direct 3D**
 - 3D API from MS for Win OS (XBOX)
 - ANGLE library provides GL support on top of D3D
- **Mantle**
 - AMD 3D API with Low-level access → **D3D12 | GL_NG**
- **Metal**
 - Apple 3D API with low-level access
- **OpenGL Desktop/ES/WebGL**
 - GL for embedded systems, now in version 3.2
 - GLES3.2 ~ GL4.5
- **GL Next Generation → Vulkan**
 - redesign to unify OpenGL and OpenGL ES into one common API (no backward compatibility)

3D APIs

- **Direct 3D**

- Games on Windows (mostly) / XBOX
- Define 3D functionality state-of-the-art
 - OpenGL typically following
 - 3D graphic cards highly collaborative
 - Multithread programming
- Proprietary – closed source – **M\$**
- **Tested & stable – good support + tools**

- **Metal**

- Apple 3D API with low-level access
- Much in the way of **Mantle?**
 - buffer & image, command buffers, sync...
- **Lean & mean → simple + ~flexible**



**Win &
Game research**



Mac/iOS future ?

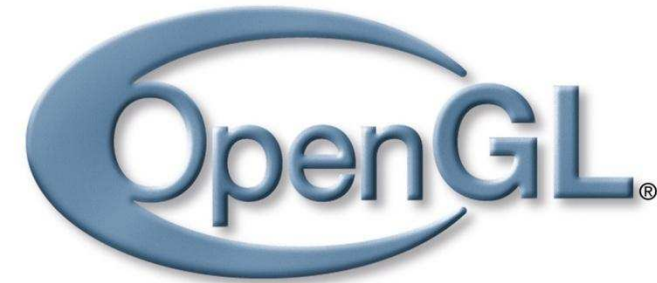
3D APIs



- **Mantle**

- AMD effort – **low level – direct access** – 3D API
- Direct control of memory (CPU/GPU) – multithreading done well
 - User-required synchronization
- **API calls per frame <3k → 100K**
- Resources: buffer & image 😊
- Simplified driver → maintenance (vendors)
 - High level API/Framework/Engines will be developed 😊
- Pipeline state
 - shaders + targets (depth/color...) + resources + geometry
- **Command queues + synchronization**
 - Compute / Draw / DMA(mem. Copy)
- Bindless – shaders can refer to state resources
- **OpenGL NEXT seems to move into ‘Mantle direction’**
- **Direct 3D 12 already pursuing low-level access**

3D APIs



- **OpenGL (Desktop/ES/WebGL)**
 - Open / research / cross-platform
 - Lagging in front of D3D → Legacy support ☹
 - No more **FIXED PIPELINE (1992)!!** -- scientific visualization...
 - GLSL (2003)...GL 3.1(2009) → deprecation/no fixed pipeline
 - Compatibility profile → legacy again...(till GL 4)
 - Core profile
 - GLSL → shader required
 - VAO
 - » group of VBO
 - » we need a base VAO for using VBO!
 - Simplifying → VBO + GLSL only!

3D APIs

- OpenGL ES 1.1
 - Fixed pipeline – no glBegin/End – no GL_POLYGON -- VBO
- OpenGL ES 2 (OpenGL 1.5 + GLSL) ~ GL4.1
 - No fixed pipeline (shaders mandatory), ETC1 texture compress..
- OpenGL ES 3 ~ GL4.3
 - Occlusion queries + geometry instancing
 - 32bit integer/float in GLSL
 - Core 3D textures, depth textures, ETC2/EAC, many formats...
 - Uniform Buffer Objects (packed shader parameters)
- OpenGL ES 3.2 ~ GL4.5
 - Compute shaders (atomics, load/store)
 - Separate shader objects (reuse)
 - Indirect draw (shader culling...)
 - NO geometry/tessellation

3D APIs

- **Vulkan**

- derived from and built upon components of AMD's Mantle API
- with respect to OpenGL
 - lower level API, more balanced CPU/GPU usage, parallel tasking, work distribution across multiple CPU cores

OpenGL	Vulkan
Global state machine	No global state
State tied to context	Command buffer instead of state
Sequential operations	Multithreaded programming
Limited control of GPU memory and sync	Explicit control of memory man. and sync
Extensive error checking	No error checking at runtime

3D APIs

- **GPGPU**
 - OpenCL
 - On Android it is not much loved
 - Use GPU vendor SDK provided libs ☺
 - On iOS is only accepted for system apps
 - Use old-school GPGPU (fragment shader -> FrameBuffer)
 - Compute shaders
 - GLES 3.2!!! **General solution!!**
 - DirectCompute on D3D

Cross-development



<http://www.appian.com/blog/enterprise-mobility-2/are-mobile-platform-choices-limiting-enterprise-process-innovation>

Cross platform

- **Unity Mobile (for gaming and VR)**
 - iOS/Android, integration with Tango
- **Unreal Engine 4 (for gaming and VR)**
 - iOS/Android
 - former Unreal Development Kit
 - free usage, payment only for shipping
- **Corona SDK**
 - iOS /Android
 - uses integrated Lua layered on top of C++/OpenGL to build graphic application
 - audio and graphics, cryptography, networking, device information and user input

Cross platform

- **Marmalade**

- iOS/Android/Windows
- two main layers
 - low level C API for memory management, file access, timers, networking, input methods (e.g. accelerometer, keyboard, touch screen) and sound and video output.
 - C++ API for higher level functionality for 2D (e.g. bitmap handling, fonts) 3D graphics rendering (e.g. 3D mesh rendering, boned animation), resource management system and HTTP networking.
- Very successful but dismissing by March 2017

- **EdgeLib**

- iOS/Android/Windows
- high performance graphics engine in C++
- support for 2D graphics, 3D graphics (OpenGL ES), input and sound

Cross platform

- **JMonkey Engine**
 - Android
 - written in Java and using shader technology extensively
 - uses LWJGL as its default renderer (another renderer based on JOGL is available, supporting OpenGL 4)
- **PowerVR**
 - iOS/Android/Windows
 - a cross-platform OS and API abstraction layer, a library of helper tools for maths and resource loading
 - optimized for PowerVR GPUs, with Vulkan support
- **ARM Developer Center**
 - Plenty of tools (computer vision and machine learning, OpenGL ES emulator, texture compression)

Cross-development

- **C++ use case: QtCreator**

- Qt (~supports android, iOS, windows phone, linux, windows, mac)
- Provides API abstraction for UI, in-app purchases, ~touch input
- HOWTO (i.e. android):
 - Android SDK
 - Android NDK (native C++ support, toolchain, libraries, GL, CL...)
 - Point environment variables ANDROID_SDK, ANDROID_NDK to folders
 - Create new android project
 - Play!
- Notes:
 - Go for Qt > 5.4 (touch events were tricky in previous versions)
 - Use QOpenGLWidget instead of QGLWidget
 - Enable touch events on each widget:
 - `QWidget::setAttribute(Qt::WA_AcceptTouchEvents);`

Mobile Graphics – Development

- **Conclusions**

- **1) Native + platform UI ...**

- C++ [any language] → LLVM compiler → target platform
 - Platform Framework **front-end** → **1 for each platform**
 - **Performance + flexibility**
 - Call native code from platform code (JNI, Object C, ...)

- **2) Native through framework ...**

- Qt | Marmalade ...
 - C++ code uses framework API
 - **Framework API abstracts platform API** [N platforms]
 - **BUT** less flexible integration ?

- **3) Go web → HTML5/JS ...**

- JS code + WebGL
 - ~**Free portability** (chrome / firefox / IE ... ?)
 - **BUT** performance is 0.5X at most with asm.js

Next Session

SCALABLE MOBILE VISUALIZATION

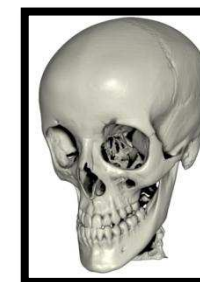
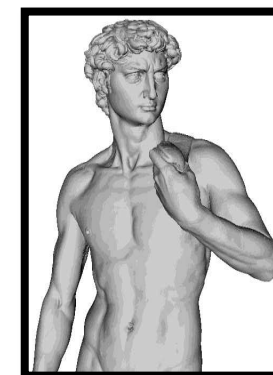
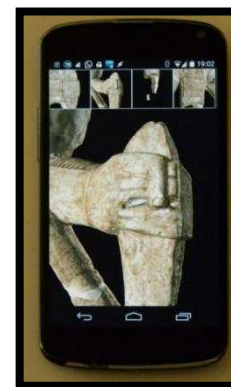
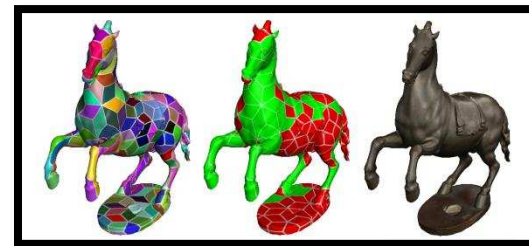
Part 4.1

Scalable Mobile Visualization: Introduction

Enrico Gobbetti, CRS4

Scalable mobile visualization

- **Goal is high quality interactive rendering of complex scenes...**
 - Large data, shading, complex illumination, ...
- **... on mobile platforms ...**
 - Mostly smartphones or tablets
 - Similar considerations can apply to other settings (e.g., embedded systems)
- **Wide variety of applications**
 - Gaming, visualization, cultural heritage...



Mobile platforms scenario

- **Typical scalable rendering problem, but with some specific constraints wrt standard (desktop settings)**
- **... screen resolutions are often extremely large (2 – 6 Mpix)**
 - Lots of pixels to generate!
- **... mobile 3D graphics hardware is powerful but still constrained**
 - Reduced computing powers, memory bandwidths, and amounts of memory wrt desktop graphics systems
 - Limited power supply!



Mobile rendering scenario

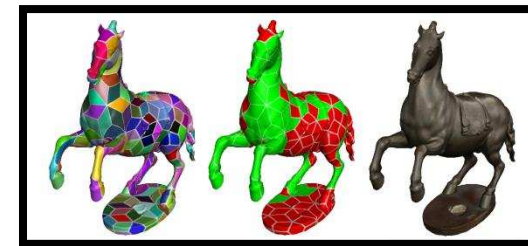
- **No brute force method applicable**
 - Need for “smart methods” to perform interactive rendering
 - Exploit at best reduced rendering power
- **Proposed solutions**
 - **Render only necessary data:** adaptive multiresolution
 - **Limit required CPU/GPU work:** full or partial precomputation
 - **Limit data requirements:** streaming approaches
 - **Exploit at best available bandwidth:** data compression



Related Work on mobile visualization

- (See previous session for details)

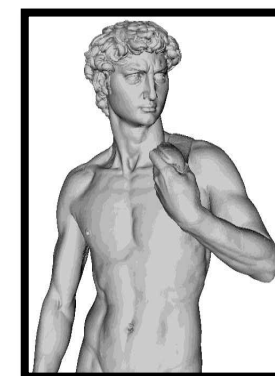
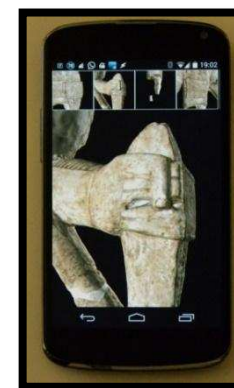
- Remote Rendering



- Local Rendering

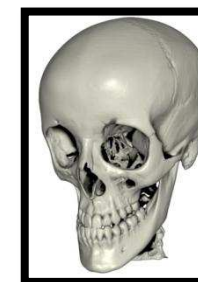
- **Model based**

- Original models
 - Multiresolution models
 - Simplified models
 - Line rendering
 - Point cloud rendering



- **Image based**

- Image impostors
 - Environment maps
 - Depth images

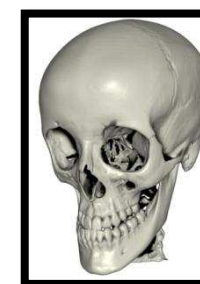
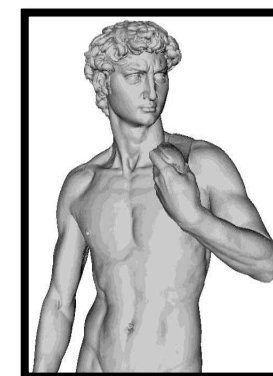
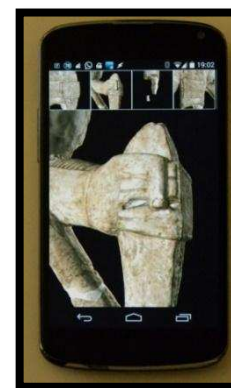
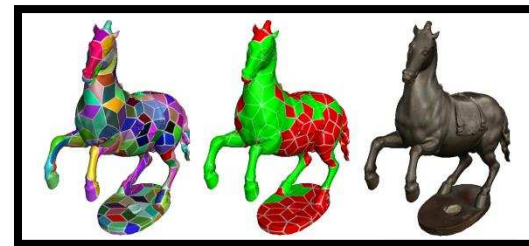


- **Smart shading**

- **Volume rendering**

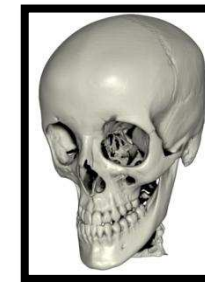
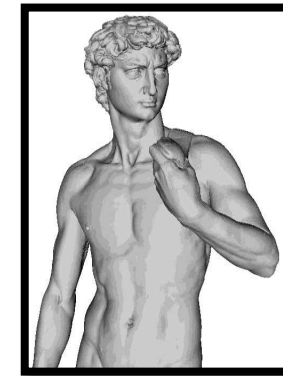
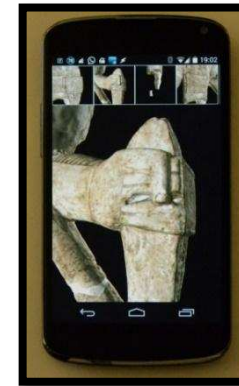
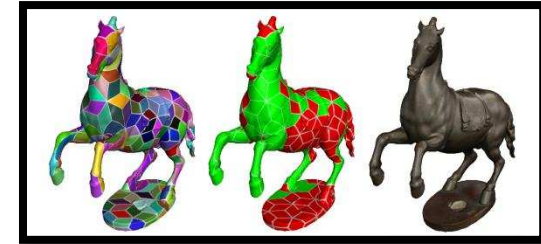
Related Work on mobile visualization

- (See previous session for details)
- Remote Rendering
 -
- Local Rendering
 - **Model based**
 - Original models
 - **Multiresolution models**
 - Simplified models
 - Line rendering
 - Point cloud rendering
 - **Image based**
 - Image impostors
 - **Environment maps**
 - Depth images
 - **Smart shading**
 - **Volume rendering**



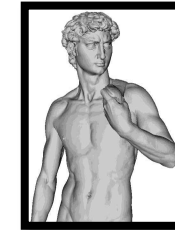
Scalable Mobile Visualization

- **Big/complex models:**
 - Detailed scenes from modeling, capturing..
 - Output sensitive: adaptive multiresolution
 - Compression / simple decoding
- **Complex rendering**
 - Global illumination
 - Pre-computation
 - Smart shading
 - Volume rendering
 - Compression / simple decoding



Scalable Mobile Visualization. Outline

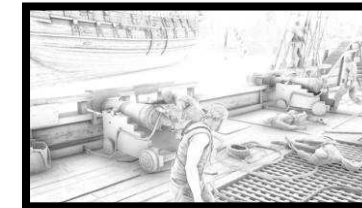
Large meshes



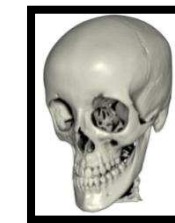
High quality illumination: full precomputation



High quality illumination: smart computation



Volume data



Part 4.2

Scalable Mobile Visualization: Large Meshes

Fabio Marton, CRS4

Scalable Mobile Visualization

Extremely
Massive
3D Models



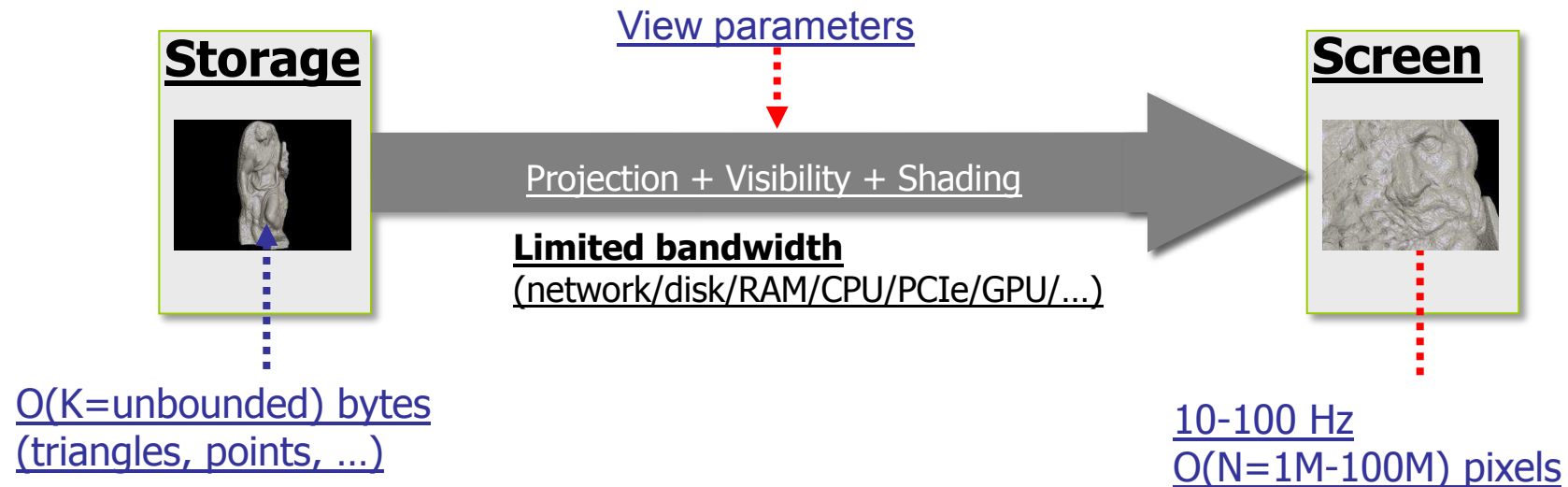
Scalable Mobile Visualization

Itty bitty living space!



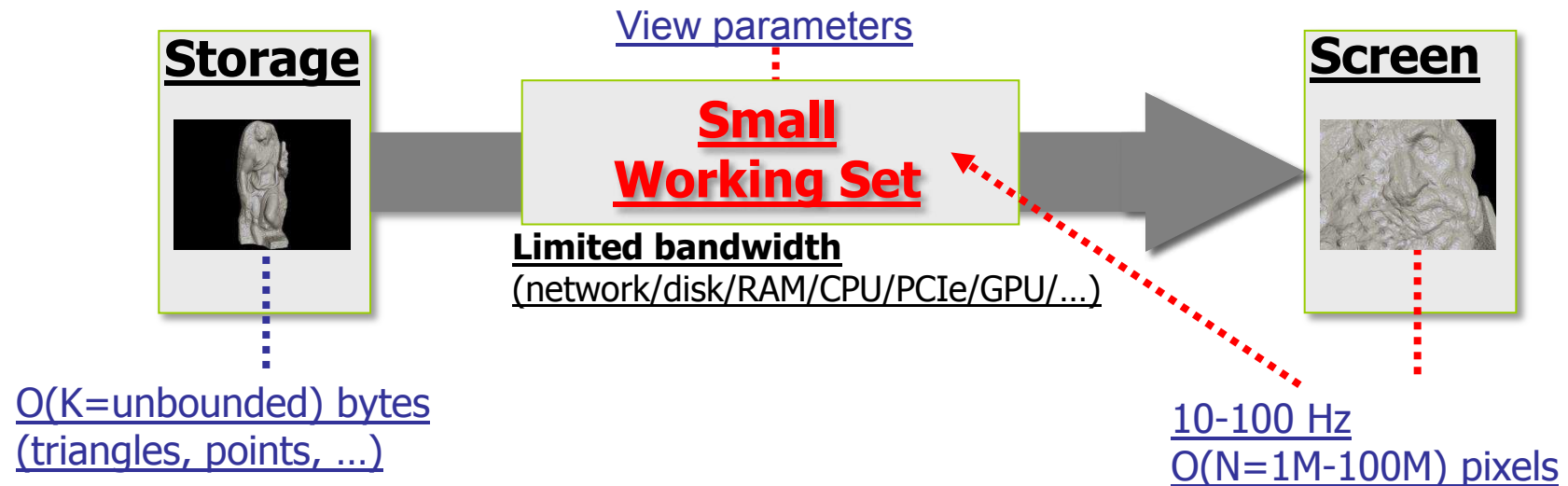
A real-time data filtering problem!

- **Models of unbounded complexity on limited computers**
 - Need for output-sensitive techniques ($O(N)$, not $O(K)$)
 - We assume less data on screen (N) than in model ($K \rightarrow \infty$)



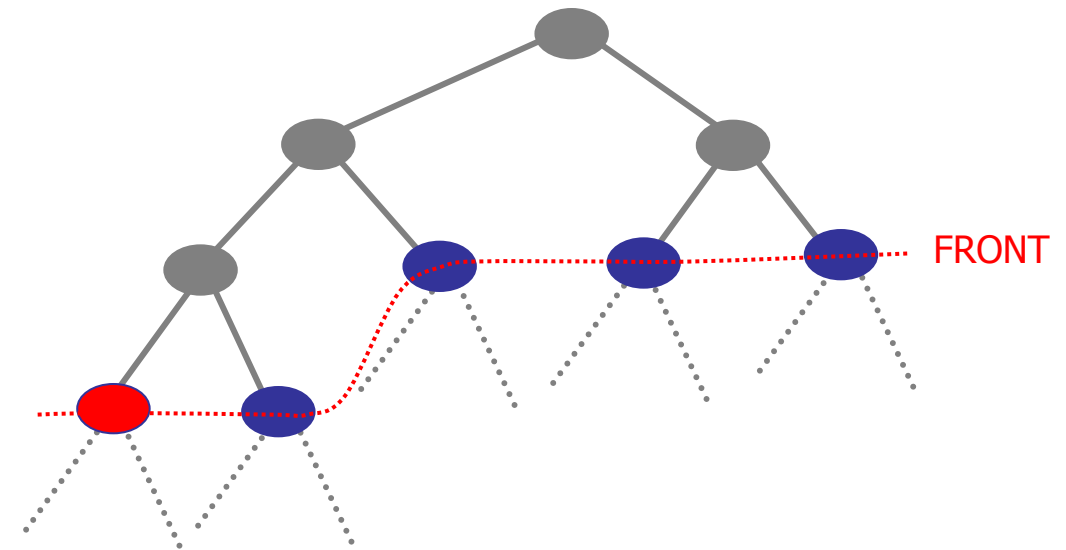
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Output-sensitive techniques

- **At preprocessing time: build MR structure**
 - Data prefiltering!
 - Visibility + simplification
 - Compression
- **At run-time: selective view-dependent refinement from out-of-core data**
 - Must be output sensitive
 - Access to prefiltered data under real-time constraints
 - Visibility + LOD



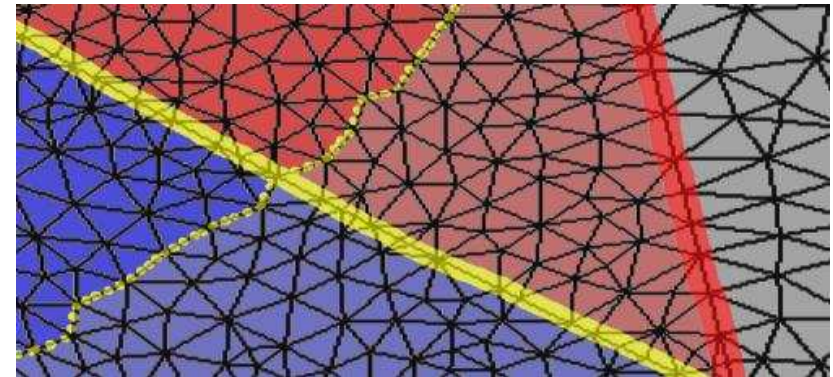
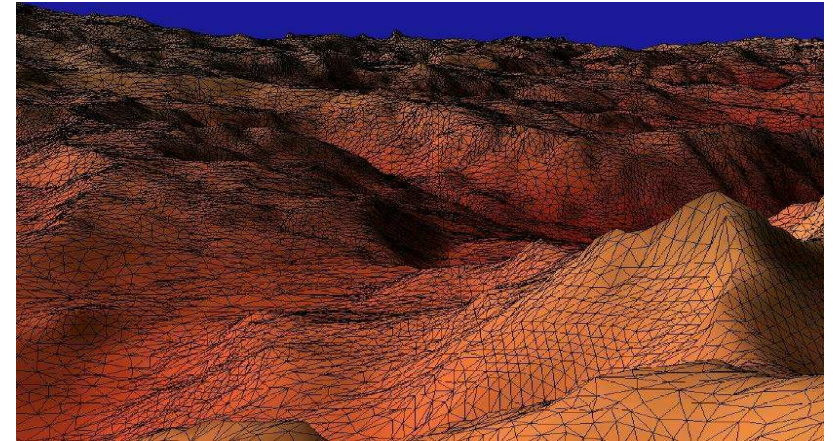
- Occluded / Out-of-view
- Inaccurate
- Accurate

Related work

- **Long history, starting with general solutions**
 - View dependent LOD and progressive streaming [Hoppe 1997]
 - Compute view dependent triangulation each frame -> CPU bound
 - Surface patches [CRS4+ISTI CNR, SIGGRAPH'04]
 - Effective in terms of speed
 - Require non-trivial data structures and techniques for decompression
 - General solutions available for Desktop environments [Cignoni et al, 2005, Yoon et al. 2008]
- **Mesh compression – MPEG-4 [Jovanova et al. 2008]**
- **Light 3D model rendering [MeshPad, PCL]**
- **Gigantic point clouds on mobile devices [Balsa et al. 2012]**
- **... and much more**

Our Contributions: chunked multiresolution structures

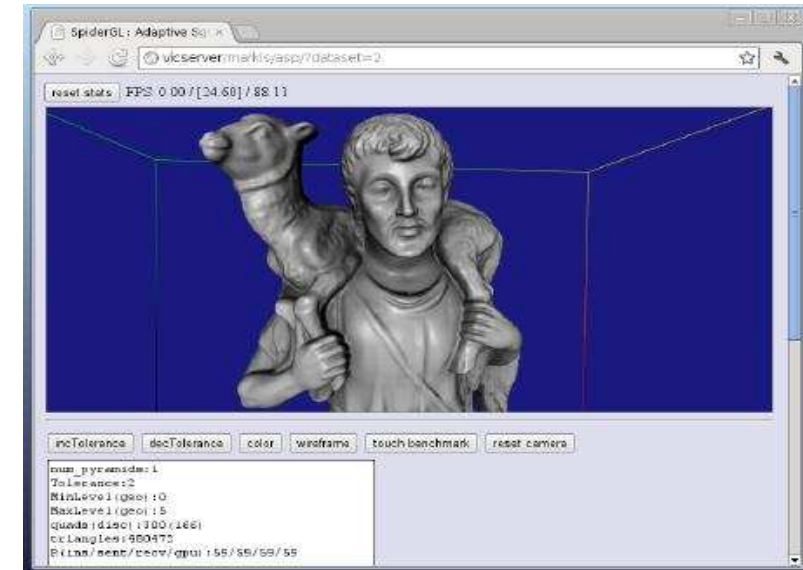
- **Efficient view-dependent meshes**
 - Approximate original surface
 - Seamless
- **Mix and match chunks**
 - Amortize CPU work!
- **Two approaches**
 - **Fixed coarse subdivision**
 - Adaptive QuadPatches
 - **Adaptive coarse subdivision**
 - Compact Adaptive TetraPuzzles



Adaptive Quad Patches

Simplified Streaming and Rendering for Mobile & Web

- **Represent models as fixed number of multiresolution quad patches**
 - Image representation allows component reuse!
 - Natural multiresolution model inside each patch
 - Adaptive rendering handled totally within shaders!
- **Works with topologically simple models**



Javascript!

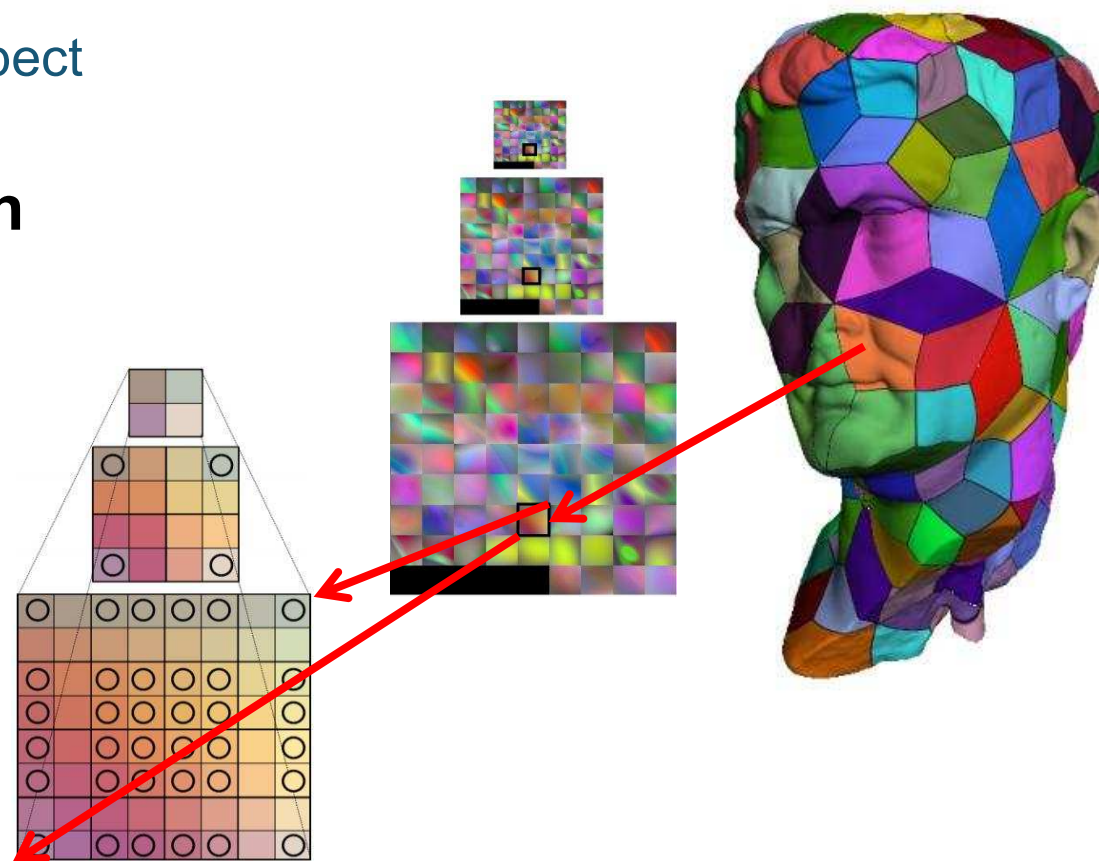
Best paper, WEB3D2012

Related work Adaptive Quad Patches

- **Geometry images [Gu et al. 2002]**
 - Exploit current GPU capabilities / optimized libraries for compression and streaming of images
- **Quad remeshing**
 - Single-disk parametrization [Floater and Hormann 2005]
 - Base mesh to parametrize the model [Petroni et al. 2010]
- **Detail rendering**
 - GPU raycasting [Oliveira et al. 2000]
 - Displacement mapping in GPU [Shiue et al. 2005]

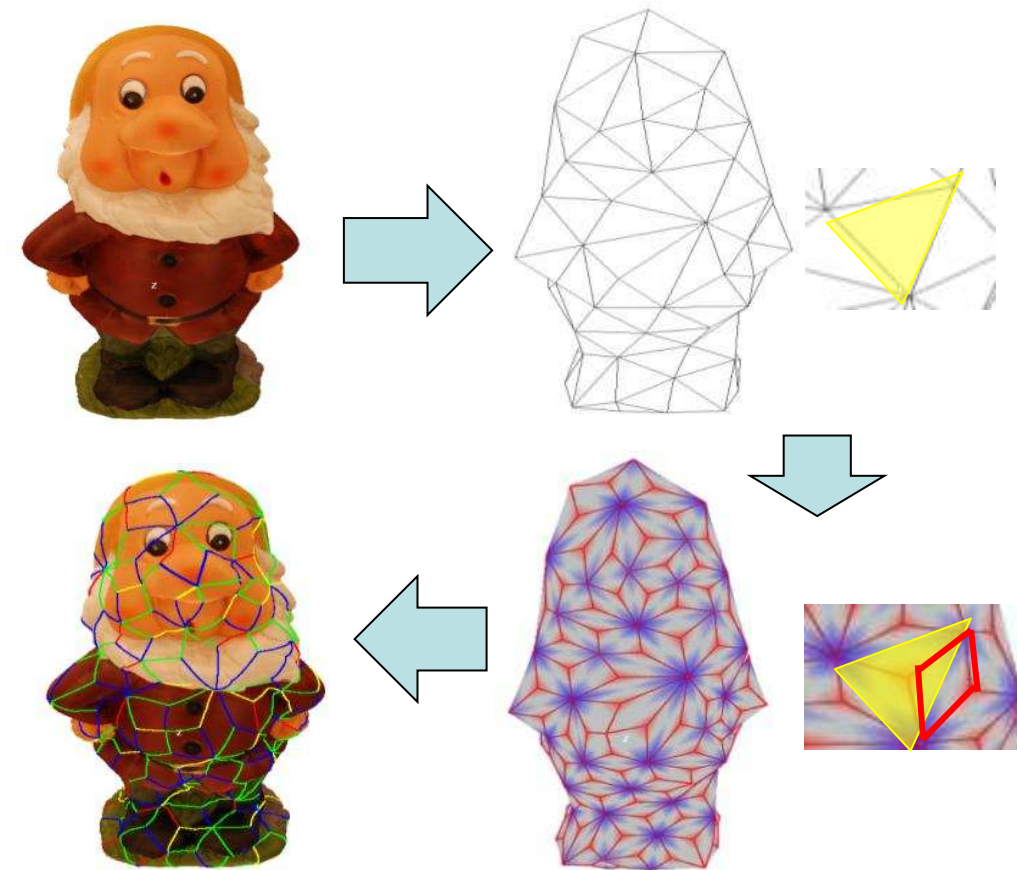
AQP Approach

- **Models partitioned into fixed number of quad patches**
 - Geometry encoded as detail with respect to the 4 corners interpolation
- **For each quad: 3 multiresolution pyramids**
 - Detail geometry
 - Normals
 - Colors
- **Data encoded as images**
 - Exploit .png (lossless compression)
- **Ensure connectivity**
 - Duplicated boundary information



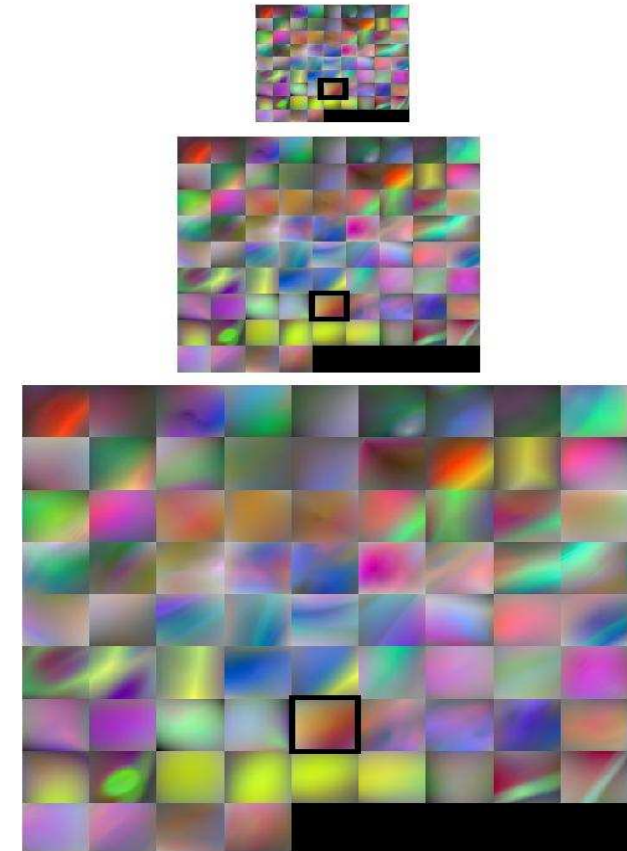
Pre-processing (Reparameterization)

- **Generate clean manifold triangle mesh**
 - Poisson reconstruction [Kazhdan et al. 2006]
 - Remove topological noise
 - Discard connected components with too few triangles
- **Parameterize the mesh on a quad-based domain**
 - Isometric triangle mesh parameterization
 - Abstract domains [Pietroni et al. 2010]
 - Remap into a collection of 2D square regions
- **Resample each quad from original geometry**
 - Associates to each quad a regular grid of samples (position, color and normal)



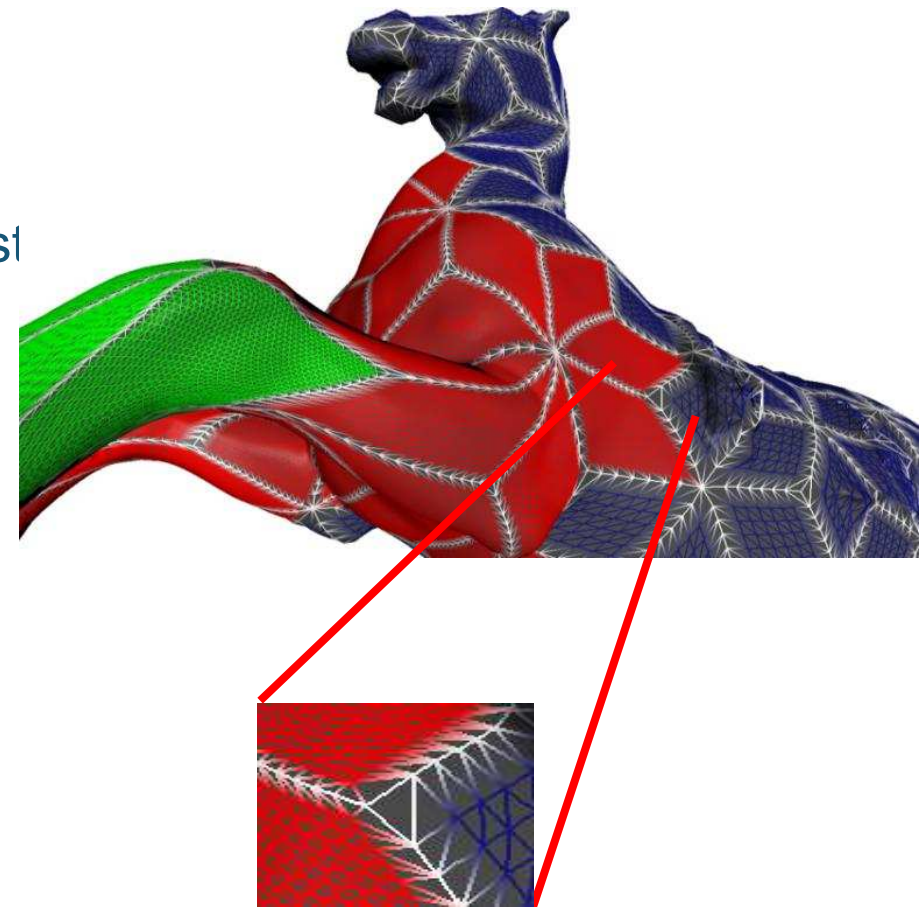
Pre-processing (Multiresolution)

- **Collection of variable resolution quad patches**
 - Coarse representation of the original model
- **Multiresolution pyramids**
 - Detail geometry
 - Color
 - Normals
- **Shared border information**
 - Ensure connectivity



Adaptive rendering

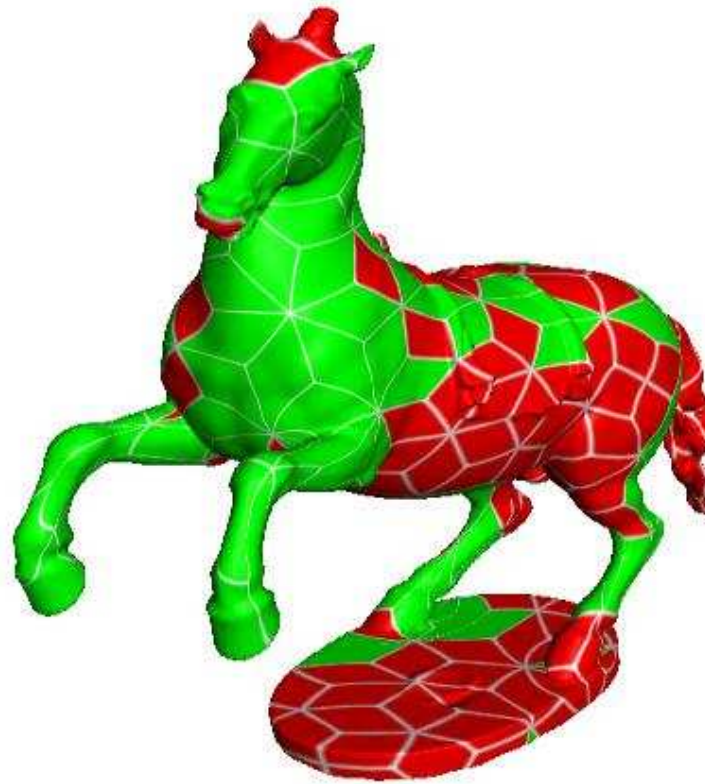
- **CPU Lod Selection**
 - Different quad LOD, but must agree on edges
 - Quad LOD = max edge LOD (available)
 - If LOD not available post asynchronous request, use finest
- **GPU drawing with Vertex Shader**
 - Quad corners
 - 1 VBO per resolution level reused (u,v)
 - texture mipmaps of
 - Displacements , Normals, Colors
 - Texture with edge LODs (snap)



Rendering example



Patches



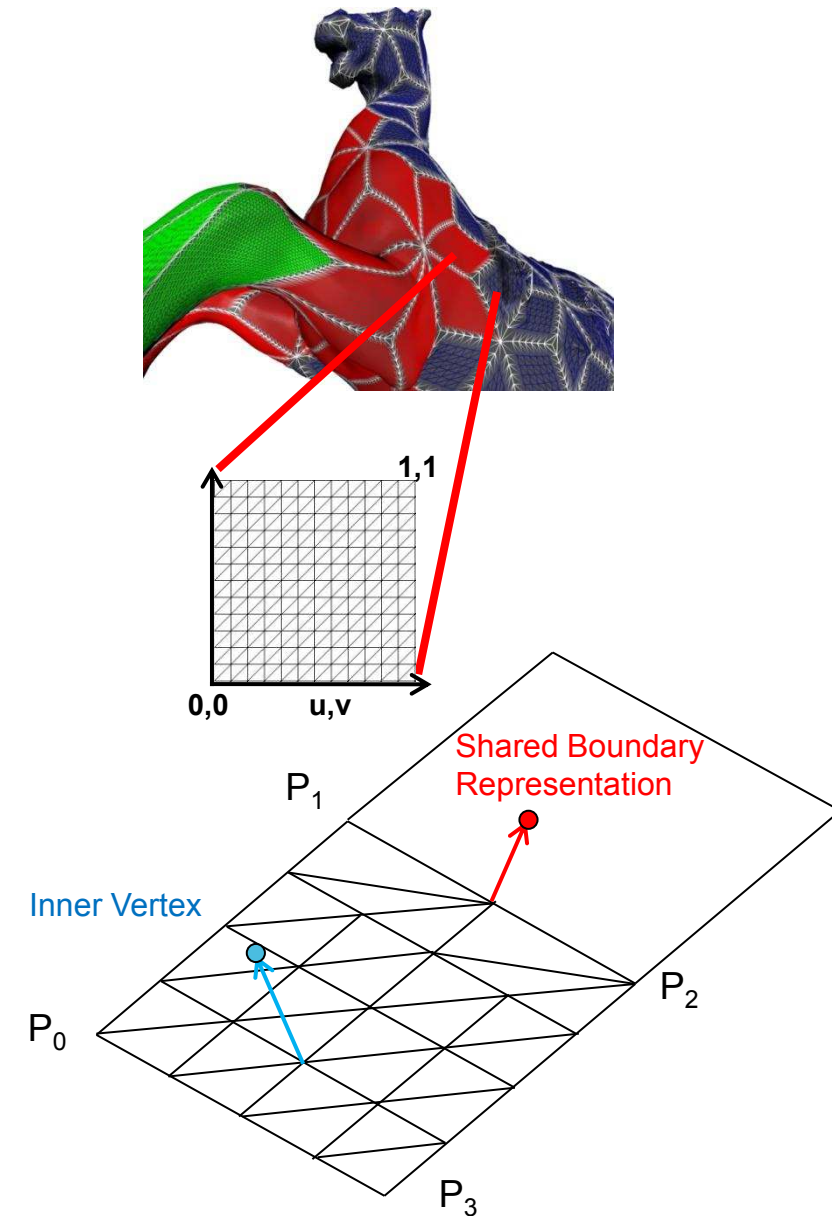
Levels



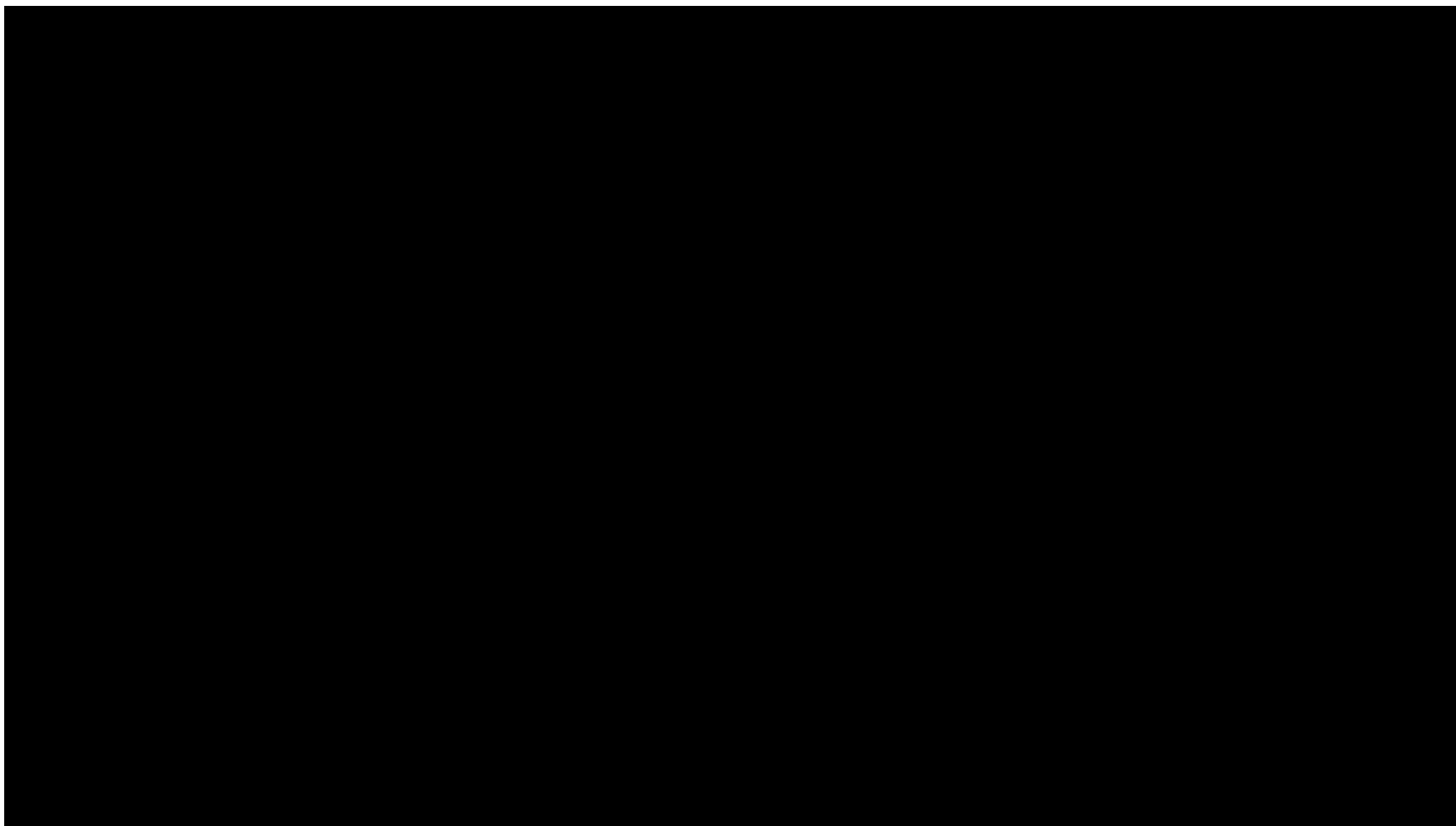
Shading

Adaptive rendering

- **1. CPU LOD Selection**
 - Find edge LODs
 - Quad LOD = max edge LODs
 - If data available use it, otherwise
 - Query data for next frames
 - Use best available representation
 - Send VBO with regular grid (1 for each LOD)
- **2. GPU: Vertex Shader**
 - Snap vertices on edges (match neighbors)
 - Base position = corner interpolation (u,v)
 - Displace VBO vertices
 - normal + displacement (dequantized)
- **3. GPU: Fragment Shader**
 - Texturing & Shading



Results



St. Matthew	374 M Tri
Avg bps	24.3 (6.3 + 9.5 + 8.5) (pos + color + normal)
Pixel Accuracy	1
FPS avg	37
FPS min	13
ADSL 8Mbps refine time	2s for model from scratch

Adaptive Quad Patches Conclusions

- **Effective creation and distribution system**

- Fully automatic
- Compact, streamable and renderable 3D model representations
- Low CPU overhead
- WebGL
 - Desktop
 - Mobile

- **Next: More general solution based on full multiresolution structure**

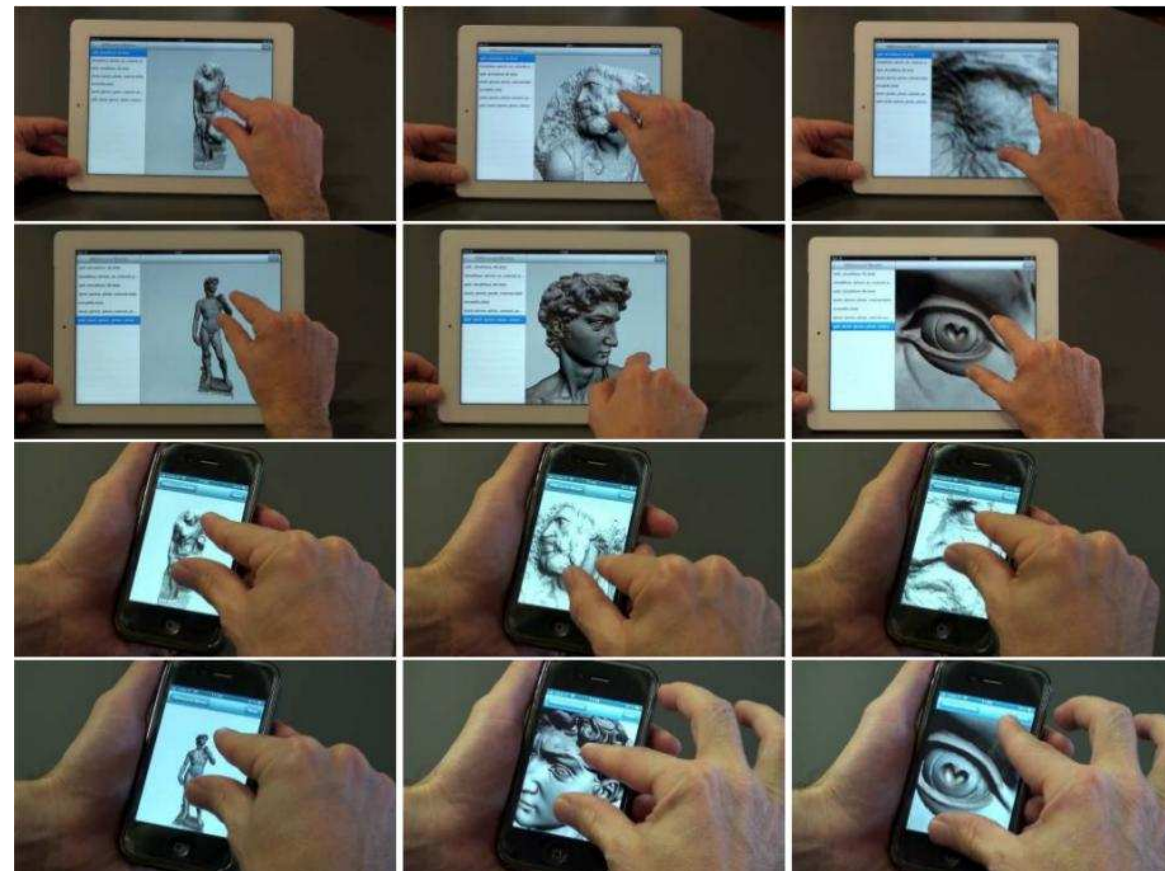
- **Limitations**

- Closed objects with large components
- Visual approximation (lossy)
- Explore more aggressive compression techniques
- Occlusion culling
- More sophisticated shading/shadowing techniques

Compact Adaptive TetraPuzzles

Adaptive multiresolution solution with compression-domain rendering

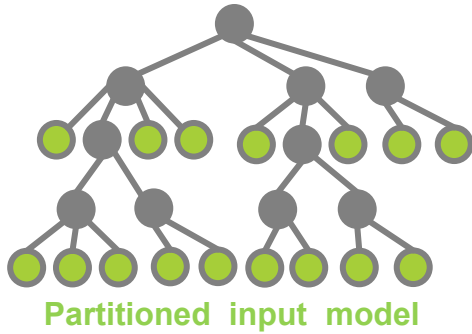
- **Represent models as variable number of multiresolution surface patches embedded in a hierarchy of tetrahedra**
 - Regular conformal hierarchy of tetrahedra spatially partitions input mesh
 - Mesh fragments at different resolutions associated to implicit diamonds
 - Fully adaptive and seamless 3D mesh structure with local quantization
 - Geometry clipped against containing tetrahedra
 - Barycentric coordinates used for local tetrahedra geometry reparameterization
 - GPU friendly compact data representation
- **Works with general surface models**



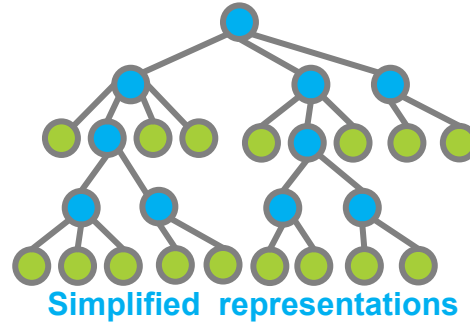
Compact Adaptive Tetra Puzzles



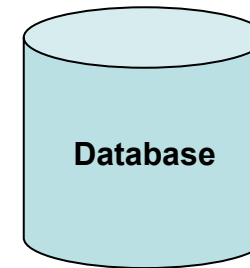
Triangle soup



Tetrahedra hierarchy



Tetrahedra hierarchy



Partitioning

Merging & Simplification

Encoding & Compression



Related work (Compression)

- **Topology coding**
 - Theoretical minimum [Rossignac 2001]
 - 1.62 bits/triangle, 3.24 bits/vertex
 - 8 bpt/16 bpv [Chhugani et al. 2007]
 - HW-implementation
 - 5 bpt/10 bpv [Meyer et al. 2012]
 - CUDA implementation
- **Attribute quantization**
 - Global position quantization [Lee et al. 2009]
 - Local quantization techniques [Lee et al. 2010]
 - Normal compression using octahedral parametrization [Meyer et al. 2010]
- **Our goal is to balance compression rate and decoding+rendering performance by using a GPU-friendly compact representation**

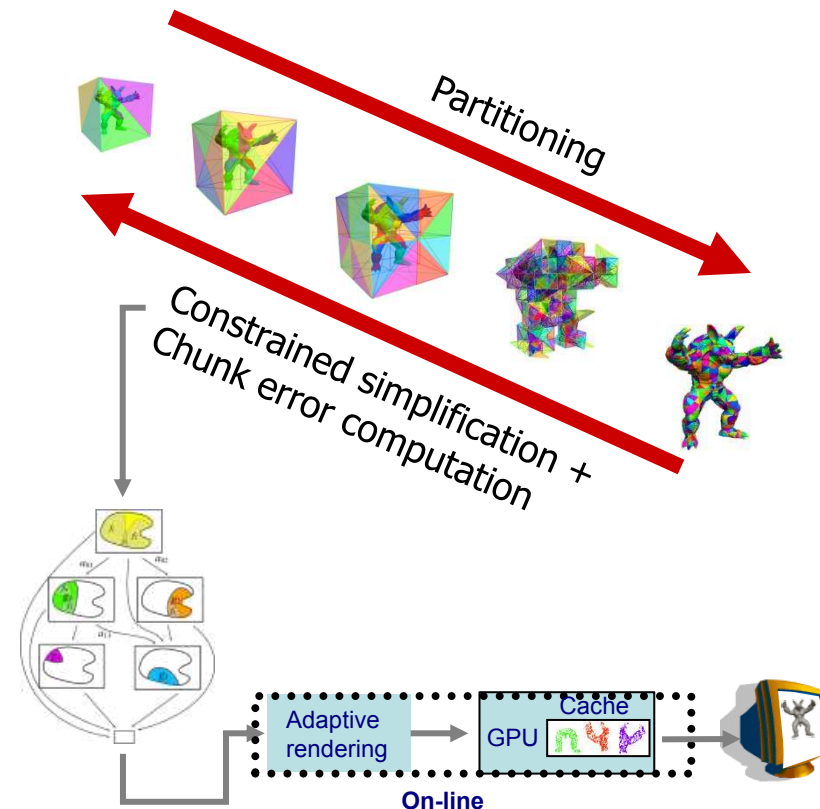
Overview

• Construction

- Start with hires triangle soup
- Partition model
- Construct non-leaf cells by bottom-up recombination and simplification of lower level cells
- Assign model space errors to cells

• Rendering

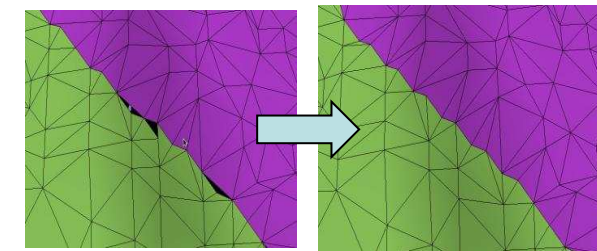
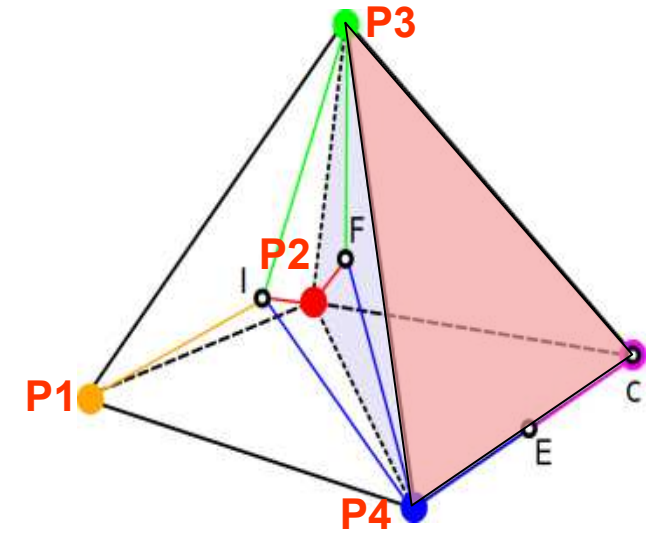
- Refine graph
- Render selected precomputed cells



Ensure continuity → Shared information on borders

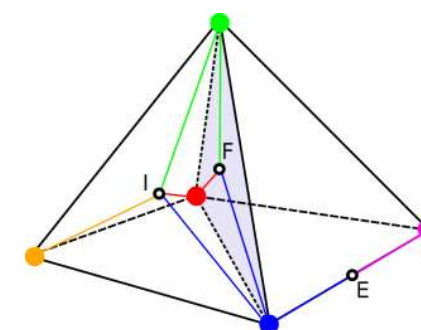
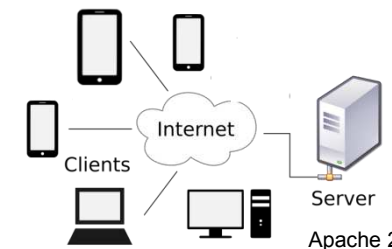
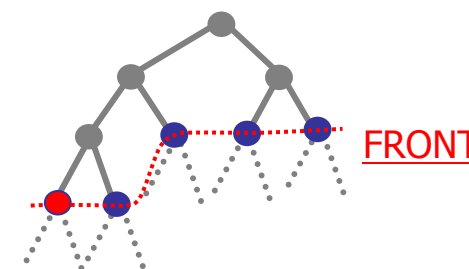
Preprocessing

- **Geometry clipped against containing tetrahedra**
- **Vertices: tetrahedra barycentric coordinates**
 - $P_{\text{barycentric}} = \lambda_1 * P_1 + \lambda_2 * P_2 + \lambda_3 * P_3 + \lambda_4 * P_4$
- **Seamless local quantization**
 - Inner vertices (I): 4 corners
 - Face vertices (F): 3 corners
 - Edge vertices (E): 2 corners
- **GPU friendly compact data representation**
 - 8 bytes = position (3 bytes) + color (3 bytes) + normal (2 bytes)
 - Normals encoded with the octahedron approach [Meyer et al. 2012]
- **Further compression with entropy coding**
 - exploiting local data coherence

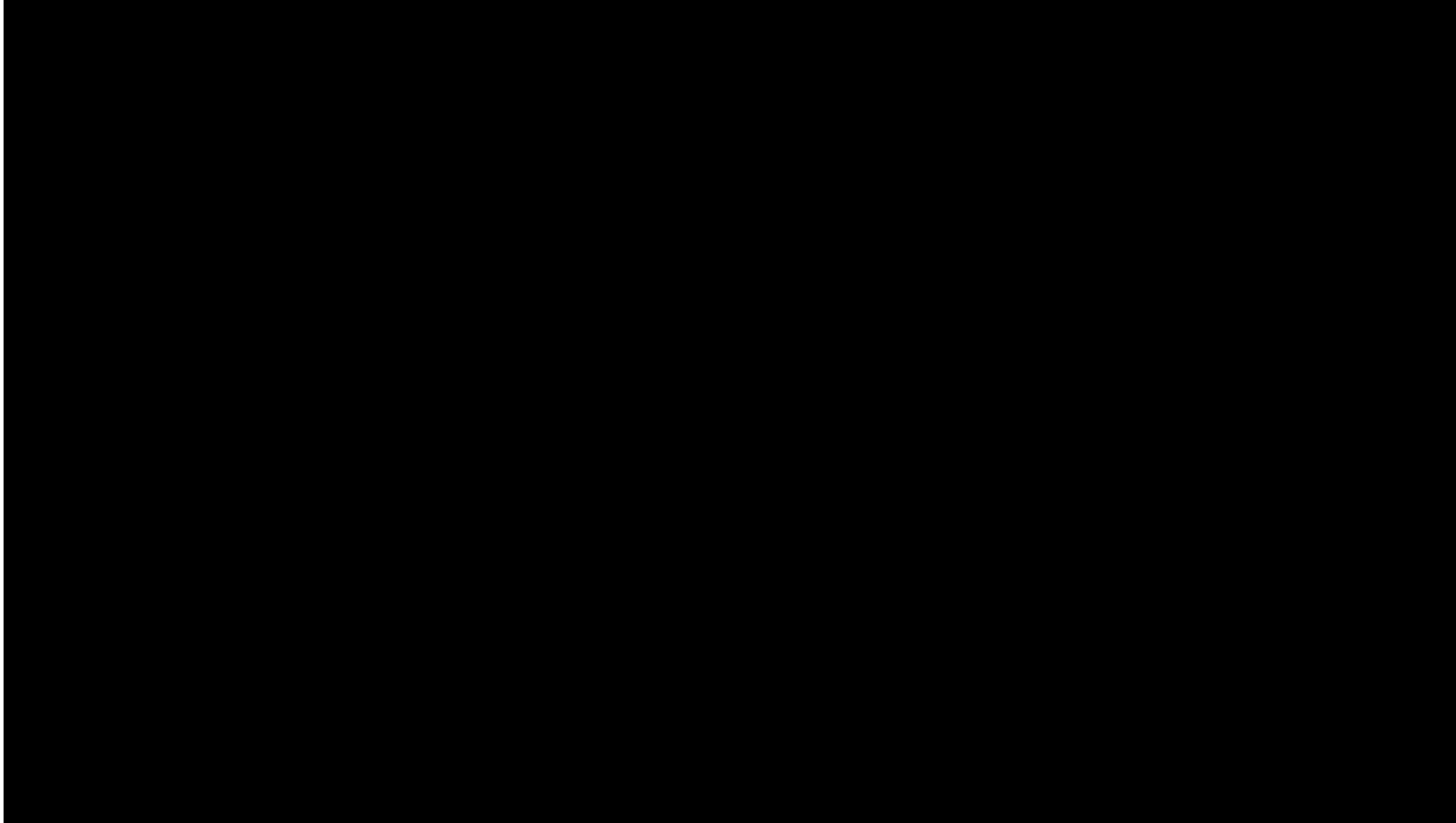


Rendering process

- **Extract view dependent diamond cut (CPU)**
- **Request required patches to server**
 - Asynchronous multithread client
 - Apache 2 based server (data repository, no processing)
- **CPU entropy decoding of each patch**
- **For each node (GPU Vertex Shader):**
 - VBO with barycentric coordinates, normals and colors (64 bpv)
 - Decode position : $P = MV * [C0 \ C1 \ C2 \ C3] * [Vb]$
 - Vb is the vector with the 4 barycentric coords
 - C0..C3 are tetrahedra corners
 - Decode normal from 2 bytes encoding [Meyers et al. 2012]
 - Use color coded in RGB24



Results

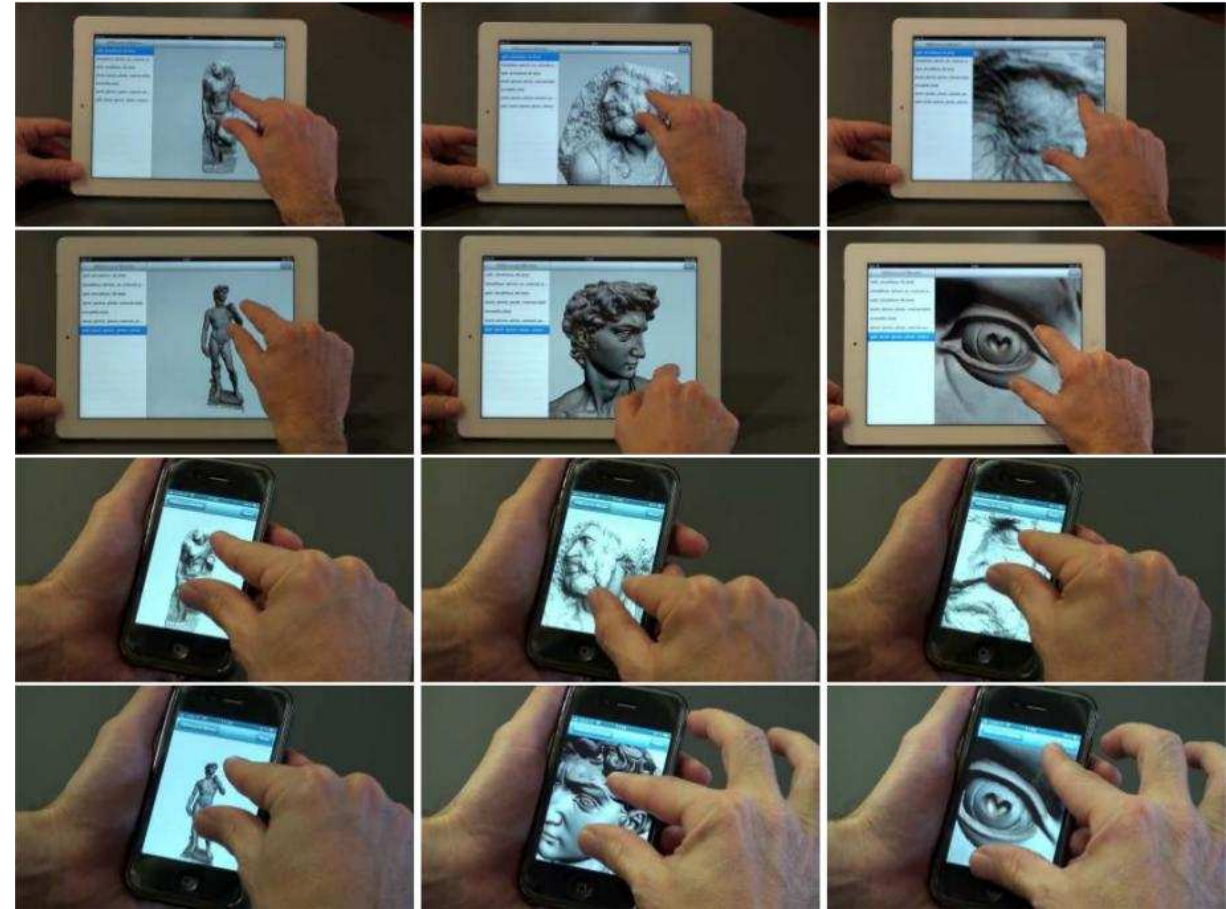


- **Input Models**
 - St. Matthew 374 MTri
 - David 1GTri
- **Compression:**
 - 40 to 50 bits/vertex
- **Streaming full screen view**
 - 30s on wireless,
 - 45s on 3G
 - David 14.5MB (1.1 Mtri)
 - St. Matthew 19.9MB (1.8 Mtri)

Rendering	iPad gen3	iPhone 4
Pixel tolerance	3	3
Triangle throughput	30 Mtri/s	2.8 Mtri/s
FPS avg	35	10
FPS refined views	15	2.8
Triangle Budget	2 M	1 M

Conclusions: Compact ATP

- **Generic gigantic 3D triangle meshes on common handheld devices**
 - Compact, GPU friendly, adaptive data structure
 - Exploiting the properties of conformal hierarchies of tetrahedra
 - Seamless local quantization using barycentric coordinates
 - Two-stage CPU and GPU compression
 - Integrated into a multiresolution data representation
- **Limitations**
 - Requires coding non-trivial data structures
 - Hard to implement on scripting environments



Conclusions: large meshes

- **Various solutions for large meshes**
- **Constrained solution: Adaptive Quad Patches**
 - Simple and fast
 - Good compression
 - Works on topologically simple models
- **General solution: Compact Adaptive Tetra Puzzles**
 - Compact data representation
 - More complex code

Part 4.3

Scalable Mobile Visualization: Introduction to complex lighting

Enrico Gobbetti, CRS4

Complex scenes

- **We have seen how to deal with complex meshes $O(Gtri)$**
 - Similar solutions for point clouds...
- **Problem tackled was size**
 - Solution proposed: adaptive multiresolution chunk-based approaches
 - Various optimized solutions to select chunks, compose them, ...
- **Rendering was simple, though**
 - One pass streaming, direct illumination
- **How to deal with more complex illumination and shading?**

Complex scenes

- **Complex illumination/shading introduce data and computation problems**
 - Non-local effects (global illumination, shadows, ...) require scattered information
 - Illumination/shading is costly (CPU/GPU time) and requires data-intensive algorithms
- **Proposed solutions in the mobile world**
 - **Full precomputation**
 - Images computed off-line
 - Removes real-time timing constraints, but introduces other problems (which images to compute? How to navigate in an image-based scene?)
 - **Smart computation**
 - Partial precomputation of some intermediate results, approximation tricks
 - Not general solution but improves quality!
- **Next session illustrates examples of full/smart computation in mobile graphics**

Part 4.4

Scalable Mobile Visualization: Full precomputation of complex lighting

Fabio Marton, CRS4

Ubiquitous exploration of scenes with complex illumination

- **Real-time requirement: ~30Hz**
 - Difficulties handling complex illumination on mobile/web platforms with current methods
- **Image-based techniques**
 - Constraining camera movement to a set of fixed camera positions
 - Enable pre-computed photorealistic visualization
- **Explore-Maps: technique for**
 - Scene representation as set of probes and arcs
 - Precomputed rendering for probes and transitions

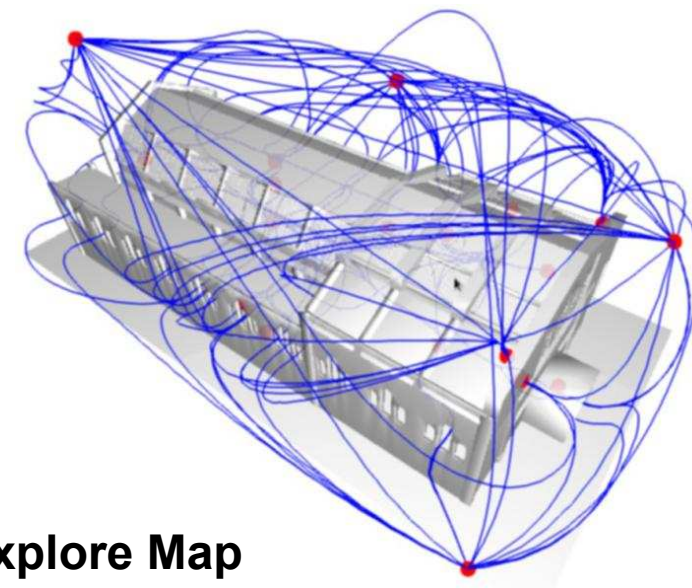


Scene Discovery

- **ExploreMaps: Automatic best view/best path methods for generating**
 - Set of probes providing full model coverage
 - Probe = 360° panoramic point of view
 - Set of arcs connecting probes
 - Enable full scene navigation

Di Bendeetto et al. Eurographics 2014

ExploreMaps: Efficient Construction and Ubiquitous Exploration of Panoramic View Graphs of Complex 3D Environments.

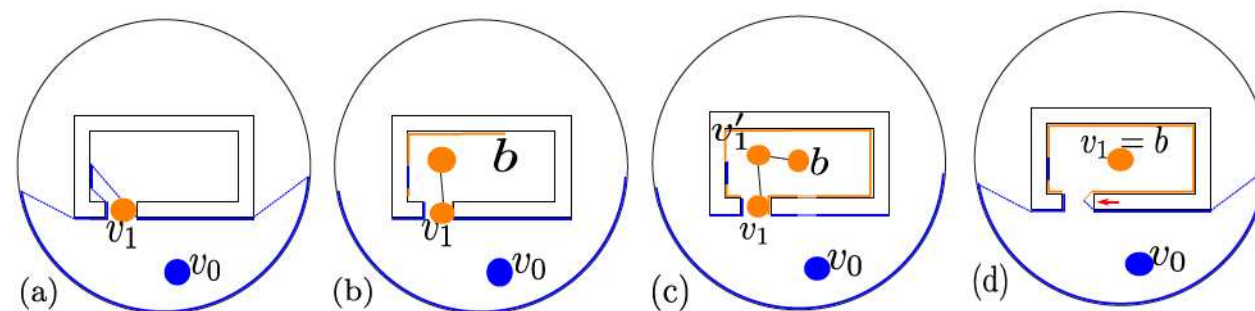
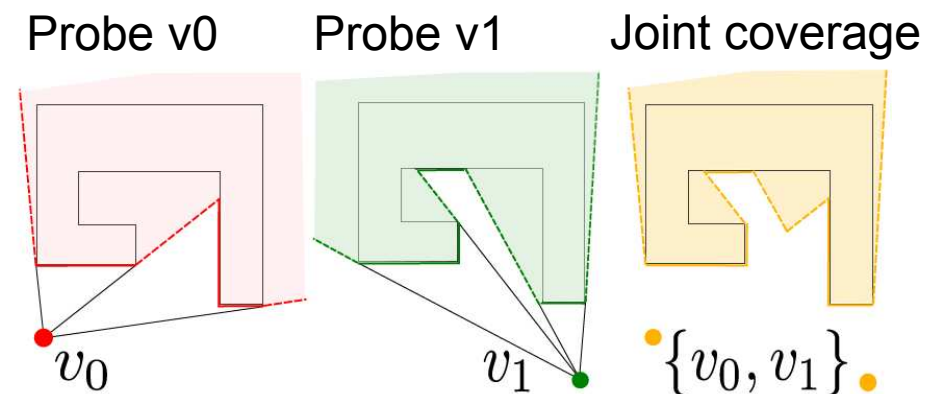


Explore Map



Best viewpoints computation

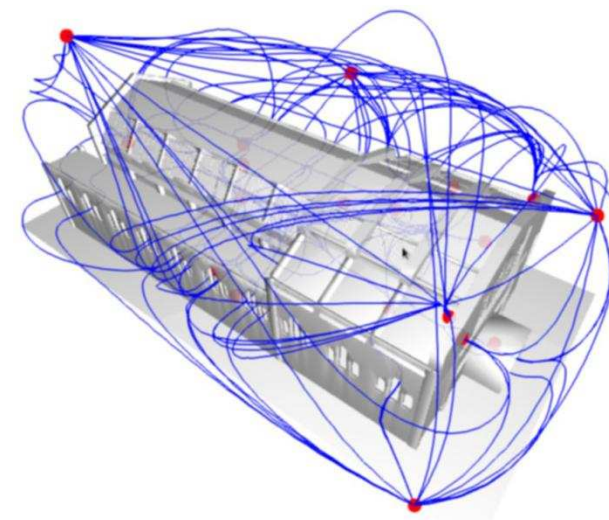
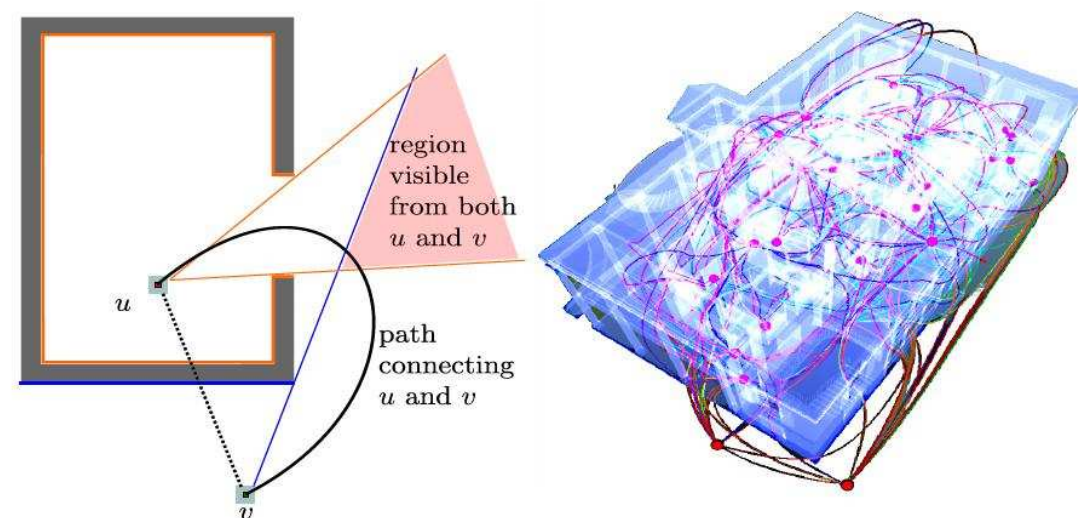
- **Position set of probes inside the scene**
 - Probes provide a 360 degree view
 - Greedy algorithm that places probes at the barycenter of newly seen geometry until all the scene is visible
 - Final clustering pass reduces number of probes



Coverage optimization, by moving to the barycenter of seen geometry

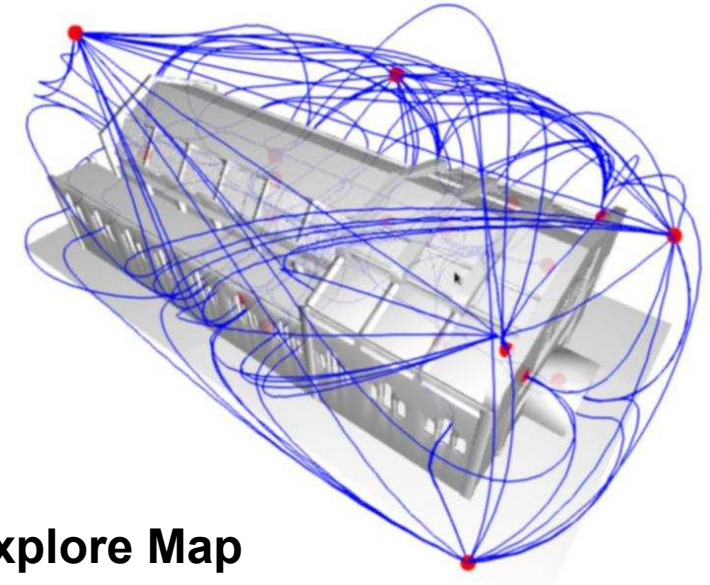
Best path computation

- **Connect probes which have a common visible region**
 - Creates a graph of probes
- **For each pair of mutually visible probe**
 - Create first path going through the closest point in the mutually visible region
 - Optimize and smooth the path using a mass-spring system



Precomputation of probe images









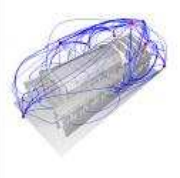

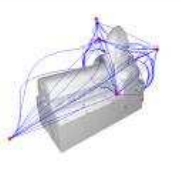

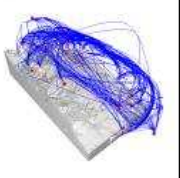

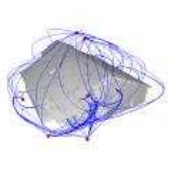

- **Compute panoramic views for probes and frames of transition arcs**
 - Photorealistic rendering (using Blender 2.68a)
 - panoramic views both for probes and transition arcs
 - 1024^2 probe panoramas
 - 256^2 transition video panoramas
 - 32 8-core PCs,
 - Rendering times ranging from 40 minutes to 7 hours/model



Explore Map

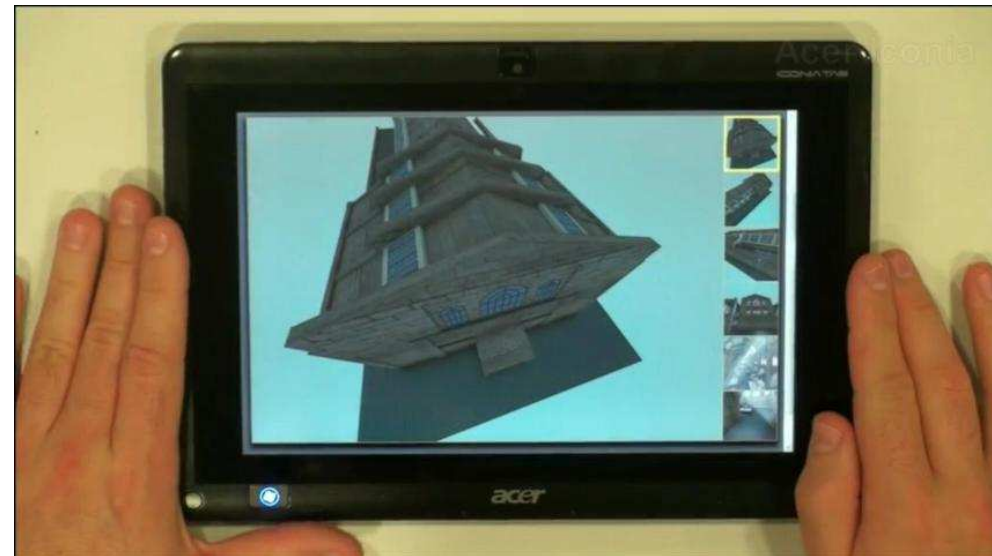
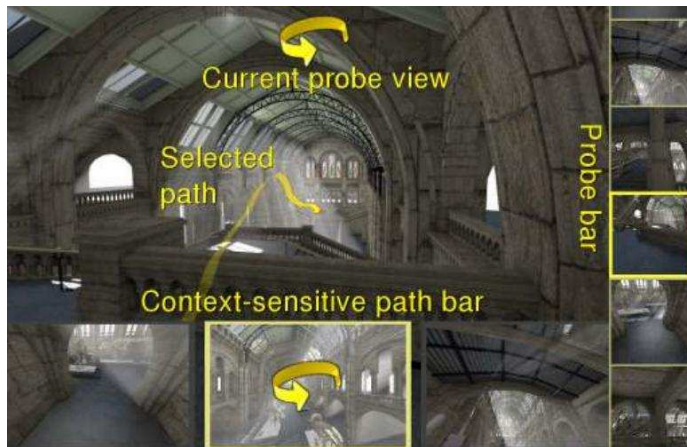


Explore Maps – Processing Results

	Museum	Sponza	Sibenik	Lighthouse	Lost Empire	Medieval Town	German Cottage	Neptune
								
								
Input								
#tri	1,468,140	262,267	69,853	48,940	157,136	14,865	79,400	2,227,359
Output								
#probes	70	36	92	57	74	78	140	79
#clusters	17	10	21	17	25	30	23	19
#paths	127	29	58	81	206	222	102	93
Time (s)								
Exploration	154	23	63	15	41	34	163	38
Clustering	17	3	27	8	13	14	118	14
Synthesis	144	35	449	453	284	395	427	279
Path	7	1	31	12	22	80	23	13
Path smoothing	3,012	122	81	89	482	199	185	150
Thumbn.	11	3	7	5	8	10	7	6
Thumbn. pos	2	2	1	1	4	4	2	1
Total	3,347	189	659	583	854	736	925	501
Storage (MB)								
Probes	59	28	72	59	86	103	79	43
Paths	248	146	113	159	371	376	390	120

Interactive Exploration

- **UI for Explore Maps**
 - WebGL implementation + JPEG + MP4
 - Panoramic images: probes + transition path
- **Closest probe selection**
 - Path alignment with current view
- **Thumbnail goto**
 - Non-fixed orientation



Conclusion: Interactive Exploration

- **Interactive exploration of complex scenes**
 - Web/mobile enabled
 - Pre-computed rendering
 - state-of-the-art Global Illumination
 - Graph-based navigation → guided exploration
- **Limitations**
 - Constrained navigation
 - Fixed set of camera positions
 - Limited interaction
 - Exploit panoramic views on paths → less constrained navigation
- **Next part of the talk:**
 - A dynamic solution for complex illumination with smart computation

Part 4.5

Scalable Mobile Visualization: Smart precomputation for complex lighting

Pere-Pau Vázquez, UPC

High quality illumination

- **Consistent illumination for AR**
- **Soft shadows**
- **Deferred shading**
- **Ambient Occlusion**

Consistent illumination for AR

- **High-Quality Consistent Illumination in Mobile Augmented Reality by Radiance Convolution on the GPU [Kán, Unterguggenberger & Kaufmann, 2015]**
- **Goal**
 - Achieve realistic (and consistent) illumination for synthetic objects in Augmented Reality environments

Consistent illumination for AR

- **Overview**

- Capture the environment with the mobile
- Create an HDR environment map
- Convolve the HDR with the BRDF's of the materials
- Calculate radiance in realtime
- Add AO from an offline rendering as lightmaps
- Multiply with the AO from the synthetic object

Consistent illumination for AR

- **Capture the environment with the mobile**
 - Rotational motion of the mobile
 - In yaw and pitch angles to cover all sphere directions
 - Images accumulated to a spherical environment map
- **HDR environment map constructed while scanning**
 - Projecting each camera image
 - According to the orientation and inertial measurement of the mobile
 - Low dynamic range imaging is transformed to HDR
 - Camera uses auto-exposure
 - Two overlapping images will have slightly different exposure
 - Alignment correction based on feature matching
 - All in the device

Consistent illumination for AR

- **Convolve the HDR with the BRDF's of the materials**
 - Use MRT to support several convolutions at once
 - Assume distant light
 - One single light reflection on the surface
 - Scene materials assumed non-emissive
 - Use a simplified rendering equation
- **Weight with AO (obtained offline)**
 - Built for real and synthetic objects
 - Need the geometry of the scene
 - Use a proxy geometry for the objects of the real world
 - Cannot be simply done on the fly

Consistent illumination for AR

- Results

Without AO



With AO



Images courtesy of Peter Kán

Consistent illumination for AR

- **Performance**

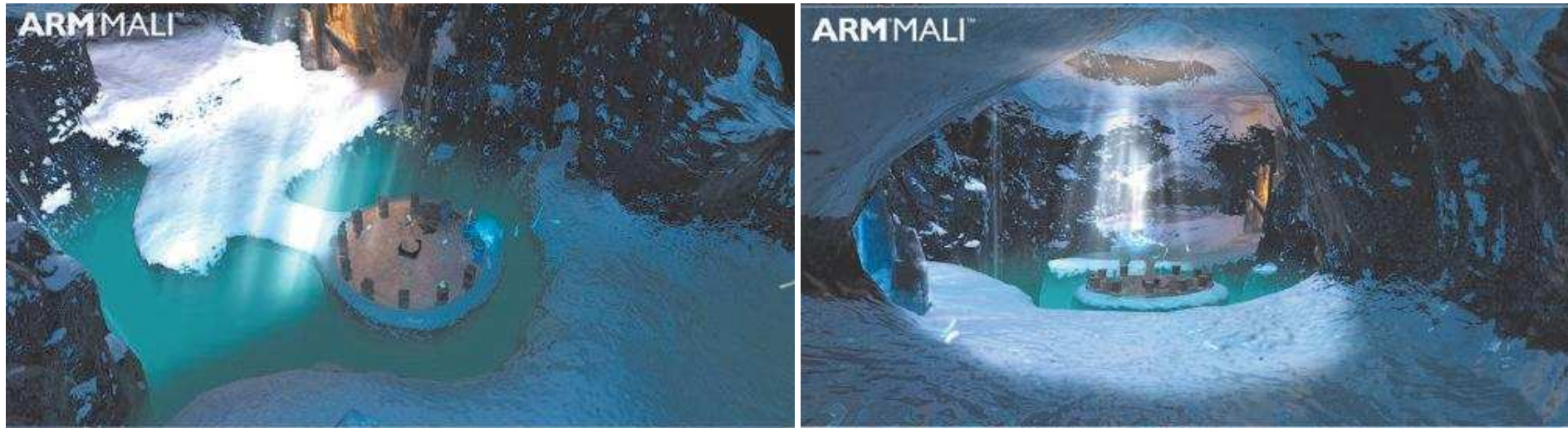
3D model	# triangles	Framerate
Reflective cup	25.6K	29 fps
Teapot	15.7K	30 fps
Dragon	229K	13 fps

- **Limitations**

- Materials represented by Phong BRDF
- AO and most shading (e.g. reflection maps) is baked

Soft shadows using cubemaps

- **Efficient Soft Shadows Based on Static Local Cubemap [Bala & Lopez Mendez, 2016]**
- **Goal**
 - Soft shadows in realtime



Taken from <https://community.arm.com/graphics/b/blog/posts/dynamic-soft-shadows-based-on-local-cubemap>

Soft shadows using cubemaps

- **Overview**
 - Create a local cube map
 - Offline recommended
 - Stores color and transparency of the environment
 - Position and bounding box
 - *Approximates the geometry*
 - Local correction
 - Using proxy geometry
 - Apply shadows in the fragment shader

Soft shadows using cubemaps

- **Generating shadows**
 - Fetch texel from cubemap
 - Using the fragment-to-light vector
 - Correct the vector before fetching
 - Using the scene geometry (bbox) and cubemap creation position
 - » To provide the equivalent shadow rays
 - Apply shadow based on the alpha value
 - Soften shadow
 - Using mipmapping and addressing according to the distance

Soft shadows using cubemaps

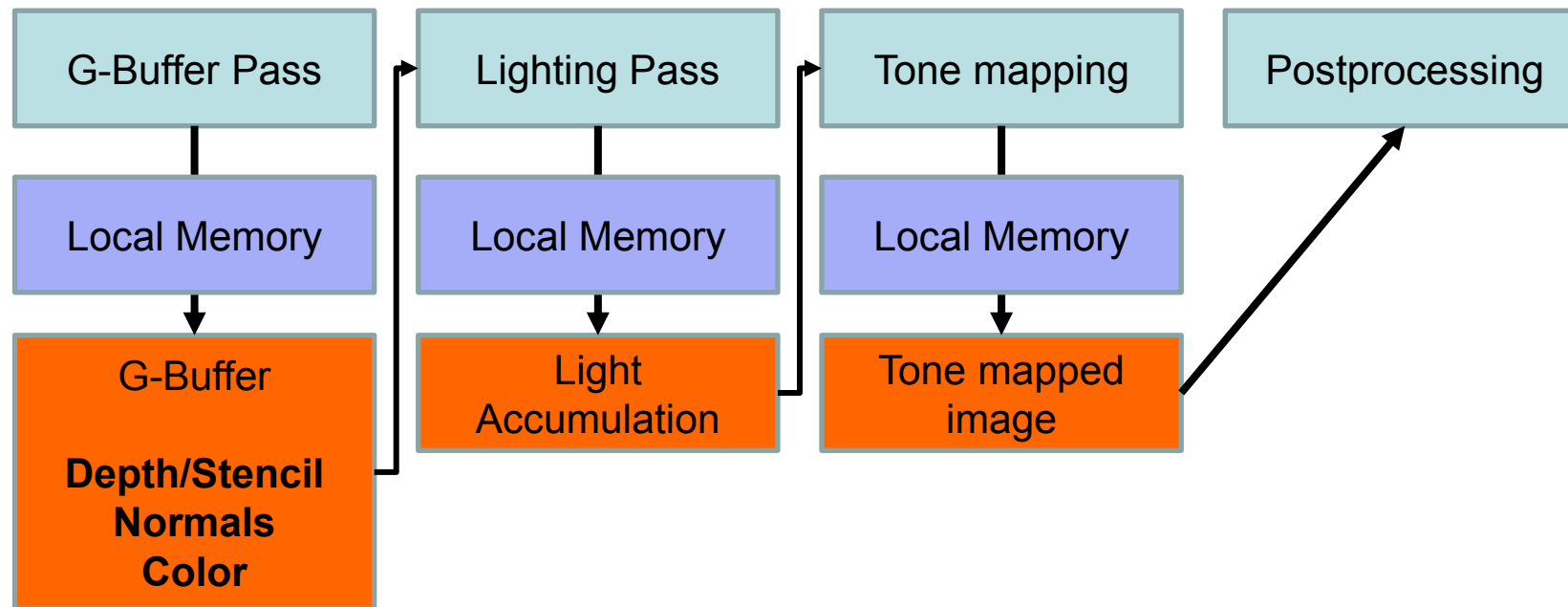
- **Conclusions**
 - Does not need to render to texture
 - Cubemaps must be pre-calculated
 - Requires reading multiple times from textures
 - Stable
 - Because cubemap does not change
- **Limitations**
 - Static, since info is precomputed

Physically-based Deferred Rendering

- **Physically Based Deferred Shading on Mobile [Vaughan Smith & Einig, 2016]**
- **Goal:**
 - Adapt deferred shading pipeline to mobile
 - Bandwidth friendly
 - Using Framebuffer Fetch extension
 - Avoids copying to main memory in OpenGL ES

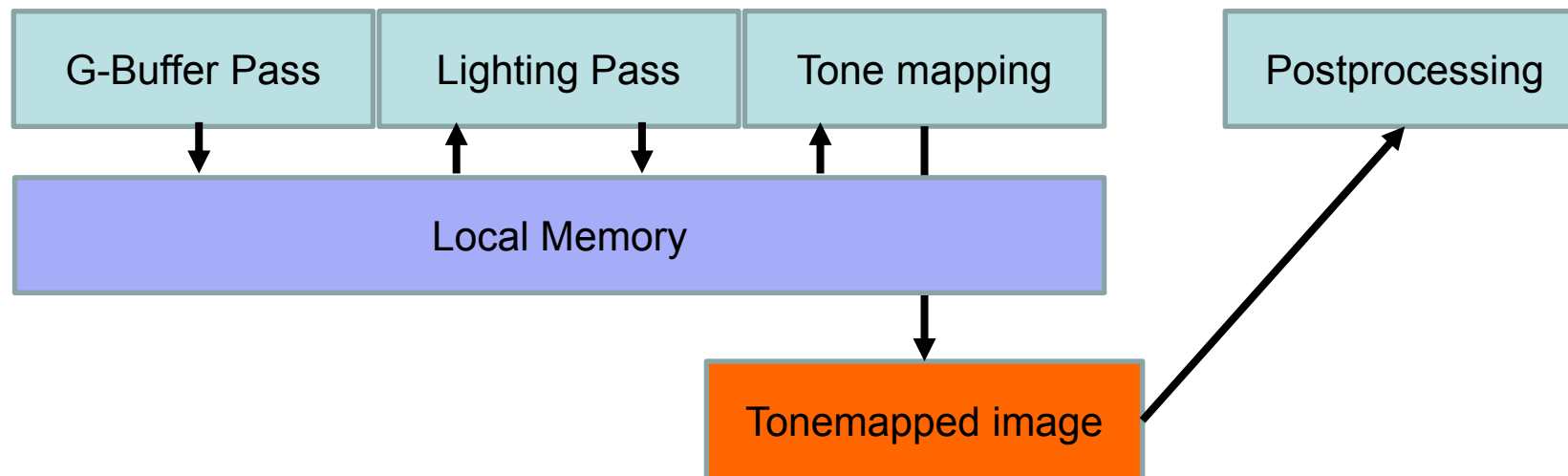
Physically-based Deferred Rendering

- **Overview**
 - Typical deferred shading pipeline



Physically-based Deferred Rendering

- **Main idea: group G-buffer, lighting & tone mapping into one step**
 - Further improve by using Pixel Local Storage extension
 - G-buffer data is not written to main memory
 - Usable when multiple shader invocations cover the same pixel
 - Resulting pipeline reduces bandwidth



Physically-based Deferred Rendering

- **Two G-buffer layouts proposed**
 - Specular G-buffer setup (160 bits)
 - Rgb10a2 highp vec4 light accumulation
 - R32f highp float depth
 - 3 x rgba8 highp vec4: normal, base color & specular color
 - Metallicness G-buffer setup (128 bits, more bandwidth efficient)
 - Rgb10a2 highp vec4 light accumulation
 - R32f highp float depth
 - 2 x rgba8 highp vec4: normal & roughness, albedo or reflectance metallicness

Physically-based Deferred Rendering

- **Lighting**
 - Use precomputed HDR lightmaps to represent static diffuse lighting
 - Shadows & radiosity
 - Can be compressed with ASTC (supports HDR data)
 - PVRTC, RGBM can also be used for non HDR formats
 - Geometry pass calculates diffuse lighting
 - Specular is calculated using Schlick's approximation of Fresnel factor

Physically-based Deferred Rendering

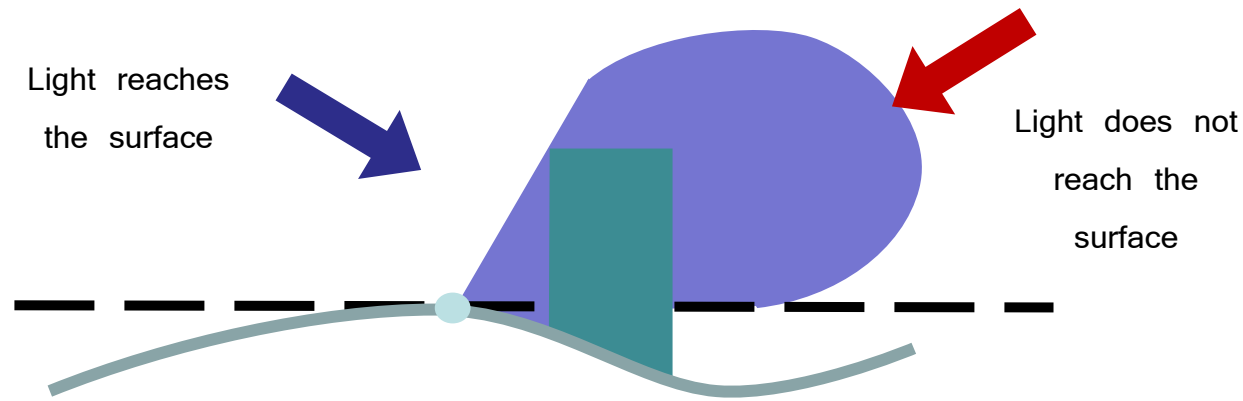
- **Results (PowerVR SDK)**
 - Fewer rendering tasks
 - meaning that the G-buffer generation, lighting, and tonemapping stages are properly merged into one task.
 - reduction in memory bandwidth
 - 53% decrease in reads and a 54% decrease in writes
- **Limitations**
 - Still not big frame rates

Ambient Occlusion in mobile

- **Optimized Screen-Space Ambient Occlusion in Mobile Devices [Sunet & Vázquez, Web3D 2016]**
- **Goal: Study feasibility of real time AO in mobile**
 - Analyze most popular AO algorithms: Crytek's, Alchemy's, Nvidia's Horizon-Based AO (HBAO), and Starcraft II (SC2)
 - Evaluate their AO pipelines step by step
 - Design architectural improvements
 - Implement and compare

Ambient Occlusion in mobile

- **Ambient Occlusion. Simplification of rendering equation**
 - The surface is a perfect diffuse surface (BRDF constant)
 - Light potentially reaches a point p equally in all directions
 - But takes into account point's visibility



$$L_o(p, \omega_o) = \frac{1}{\pi} \int_{\Omega} \rho(d(p, \omega_i)) \cos \theta_i d\omega_i$$

$$\rho(d) = \begin{cases} f(d) \in [0, 1] & d < \text{threshold} \\ 0 & \text{otherwise} \end{cases}$$

Ambient Occlusion in mobile

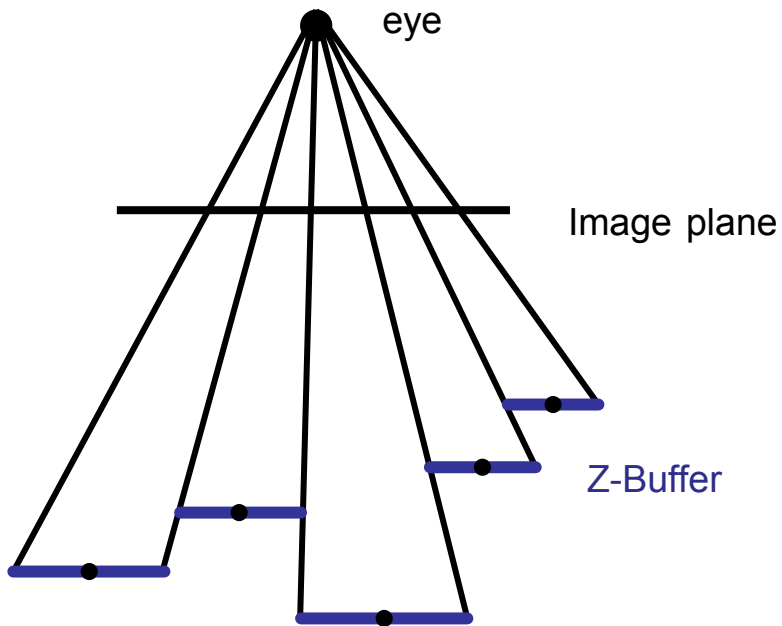
- **AO typical implementations**

- Precomputed AO: Fast & high quality, but static, memory hungry
- Ray-based: High quality, but costly, visible patterns...
- Geometry-based: Fast w/ proxy structures, but lower quality, artifacts/noise...
- Volume-based: High quality, view independent, but costly
- Screen-space:
 - Extremely fast
 - View-dependent
 - [mostly] requires blurring for noise reduction
 - Very popular in video games (e.g. Crysis, Starcraft 2, Battlefield 3...)

Ambient Occlusion in mobile

- **Screen-space AO:**

- Approximation to AO implemented as a screen-space post-processing
 - ND-buffer provides coarse approximation of scene's geometry
 - Sample ND-buffer to approximate (estimate) ambient occlusion instead of shooting rays



Assassin's Creed Syndicate



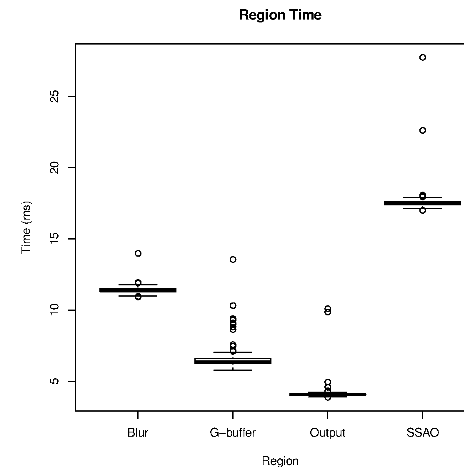
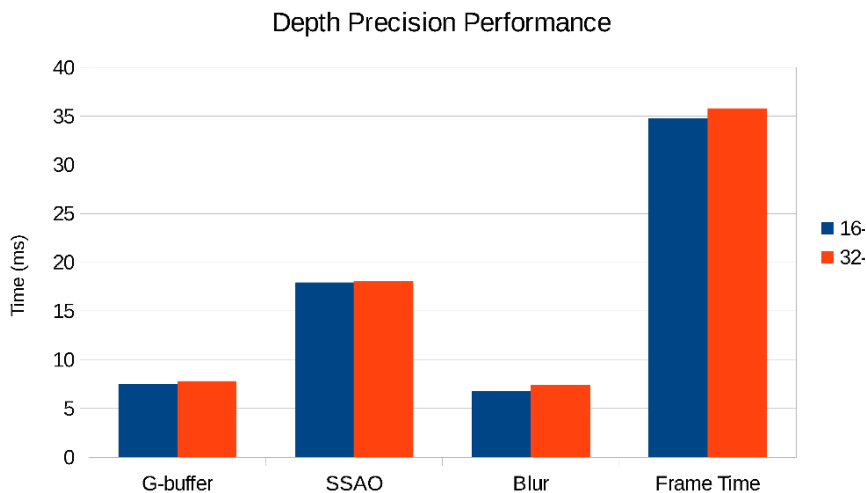
Ambient Occlusion in mobile

- **SSAO pipeline**

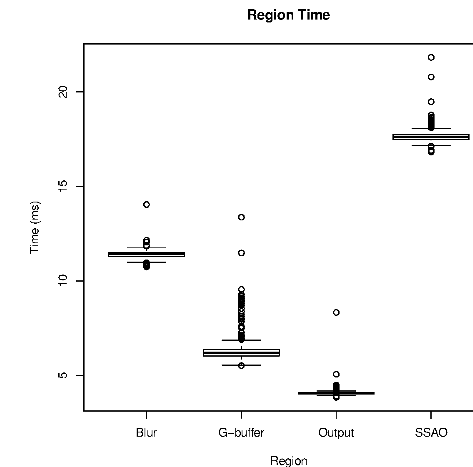
1. Generate ND (normal + depth, OpenGL ES 2) or G-Buffer (ND + RGB..., OpenGL ES 3.+)
2. Calculate AO factor for visible pixels
 - a. Generate a set of samples of positions/vectors around the pixel to shade.
 - b. Get the geometry shape (position/normal...)
 - c. Calculate AO factor by analyzing shape...
3. Blur the AO texture to remove noise artifacts
4. Final compositing

Ambient Occlusion in mobile

- **Optimizations. G-Buffer storage**
 - G-Buffer with less precision (32, 16, 8)
 - 8 not enough
 - 16 and 32 similar quality
 - Normal storage (RGB vs RG)
 - RGB normals are faster



RGB normals.



RG normals.

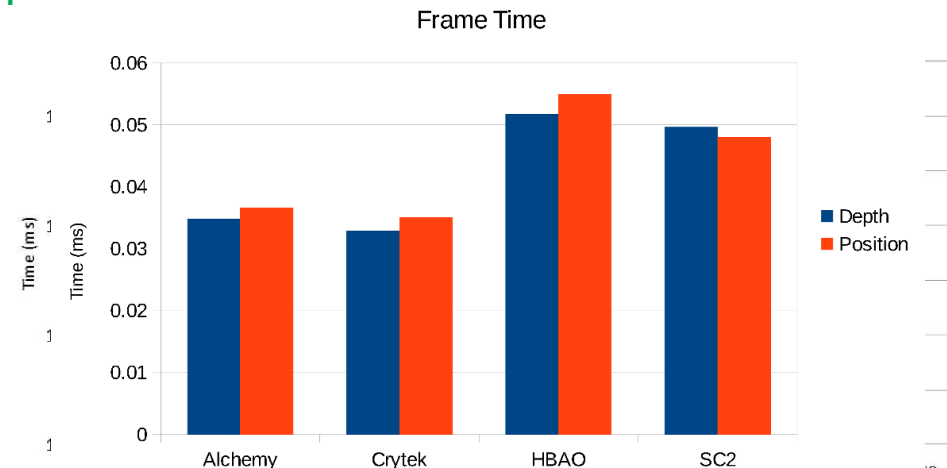
Ambient Occlusion in mobile

- **Optimizations. Sampling**

- AO samples generation (disc and hemisphere)
 - Desktops use up to 32
 - With mobile, 8 is the affordable amount
 - Pseudo-random samples produces noticeable patterns
- Our proposed solution
 - Compute sampling patterns offline
 - 2D: 8-point Poisson disc
 - 3D: 8-point cosine-weighted hemisphere (Malley's approach, as in [Pharr and Humphreys, 2010])
 - Scaling and rotating the resulting pattern ([Chapman, 2011])
 - Predictable, reproducible, robust

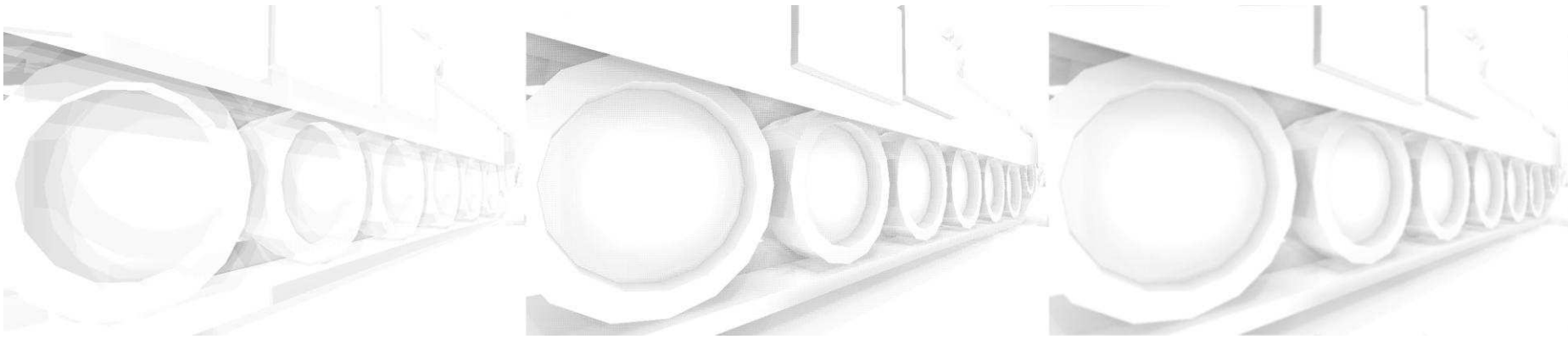
Ambient Occlusion in mobile

- **Optimizations. Getting geometry positions**
 - Transform samples to 3D
 - Inverse transform vs similar triangles
 - Precision for speed
 - Similar triangles are faster
 - Storing depth vs storing 3D positions in G-Buffer
 - Trades bandwidth for memory
 - Depth slightly better
 - Better profile for the application



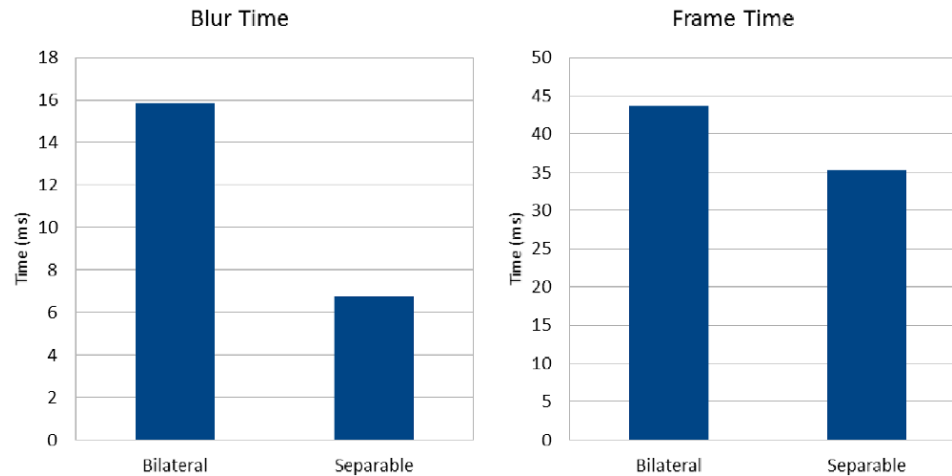
Ambient Occlusion in mobile

- **Optimizations. Banding & Noise**
 - Fixed sampling pattern produces banding (left)
 - Random sampling reduces banding but adds noise (middle)
 - SSAO output is typically blurred to remove noise (right)
 - But blurs edges



Ambient Occlusion in mobile

- **Optimizations. Banding & Noise**
 - User bilateral filter instead
 - Works better
 - Improve timings with separable filter

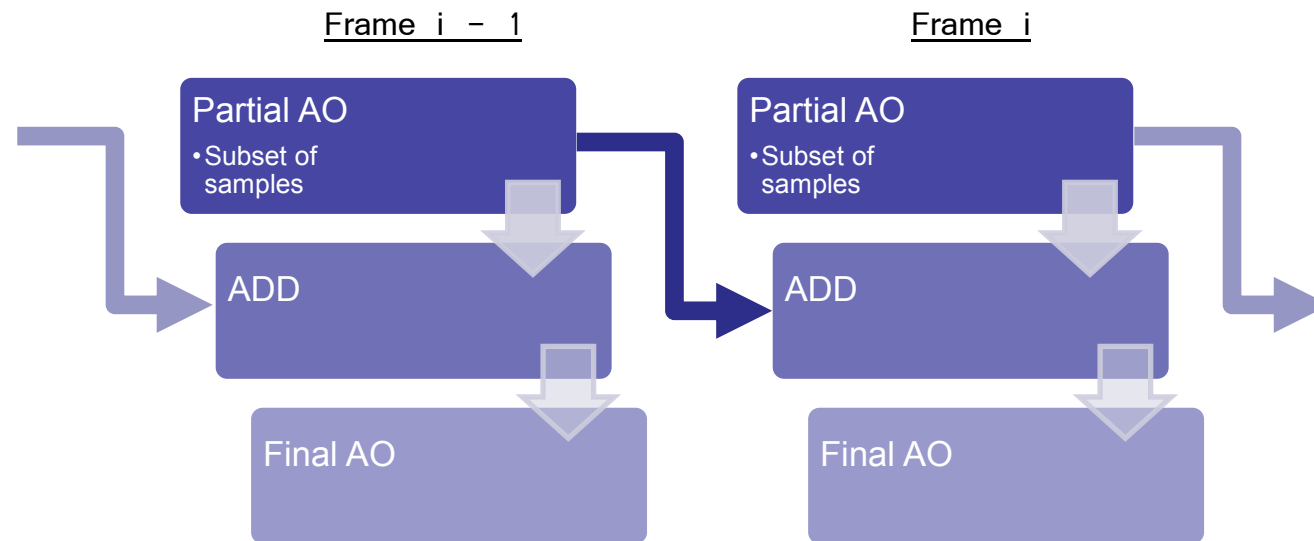


$$BF[I]_p = \frac{1}{W_p} \sum_{q \in S} G_{\sigma_s}(\|p - q\|) G_{\sigma_r}(\|I_q - I_p\|) I_q$$

$$G_{\sigma}(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

Ambient Occlusion in mobile

- **Optimizations. Progressive AO**
 - Amortize AO throughout many frames



Ambient Occlusion in mobile

- **Optimizations**
 - Naïve improvement: Reduce the calculation to a portion of the screen
 - Mobile devices have a high PPI resolution
 - Reduction improves timings dramatically while keeping high quality
 - Typical reduction:
 - Offscreen render to 1/4th of the screen
 - Scale-up to fill the screen

Ambient Occlusion in mobile

- Results

Algorithm	Optimized (not progressive)	Optimized + progressive
Starcraft 2	17.8%	38.5%
HBAO	25.6%	39.2%
Crytek	23.4%	35.0%
Alchemy	24.8%	38.2%

Ambient Occlusion in mobile

- **Conclusions**

- Developed an optimized pipeline for mobile AO
 - Analyzed the most popular AO techniques
 - Improved several important steps of the pipeline
 - Proposed some extra contributions (e.g. progressive AO)
 - Achieved realtime framerates with high quality
 - Developed techniques can be used in WebGL
- Future Work
 - Further improvement of the pipeline
 - Developing “Homebrew” method
 - With all known improvements
 - Some extra tricks
 - Not ready for prime time yet

Part 4.5

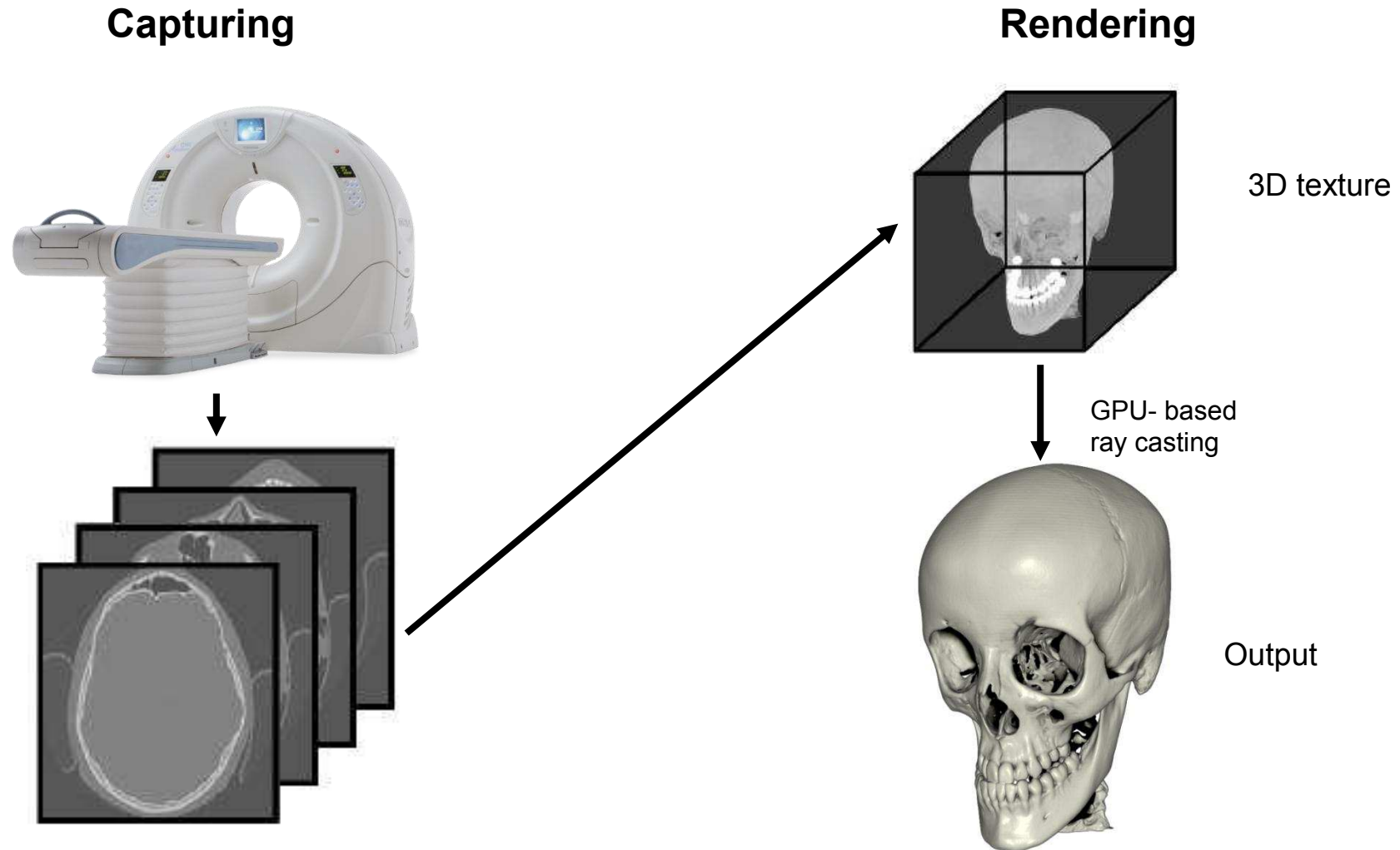
Scalable Mobile Visualization: Volumetric Data

Pere-Pau Vázquez, UPC

Rendering Volumetric Datasets

- **Introduction**
- **Challenges**
- **Architectures**
- **GPU-based ray casting on mobile**
- **Conclusions**

Rendering Volumetric Datasets



Rendering Volumetric Datasets

- **Introduction**
 - Volume datasets
 - Sizes continuously growing (e.g. $>1024^3$)
 - Complex data (e.g. 4D)
 - Rendering algorithms
 - GPU intensive
 - State-of-the-art is ray casting on the fragment shader
 - Interaction
 - Edition, inspection, analysis, require a set of complex manipulation techniques

Rendering Volumetric Datasets

- **Desktop vs mobile**
 - Desktop rendering
 - Large models on the fly
 - Huge models with the aid of compression/multiresolution schemes
 - Mobile rendering
 - Standard sizes (e.g. 512^3) still too much for the mobile GPUs
 - Rendering algorithms GPU intensive
 - State-of-the-art is GPU-based ray casting
 - Interaction is difficult on a small screen
 - Changing TF, inspecting the model...

Rendering Volumetric Datasets

- **Challenges on mobile:**
 - Memory:
 - Model does not fit into memory
 - Use client server approach / compress data
 - GPU capabilities:
 - Cannot use state of the art algorithm (e.g. no 3D textures)
 - Texture arrays
 - GPU horsepower:
 - GPU unable to perform interactively
 - Progressive rendering methods
 - Small screen
 - Not enough details, difficult interaction

Rendering Volumetric Datasets

- **Mobile architectures**
 - Server-based rendering
 - Hybrid approaches
 - Pure mobile rendering
 - Server-based and hybrid rely on high bandwidth communication

Rendering Volumetric Datasets

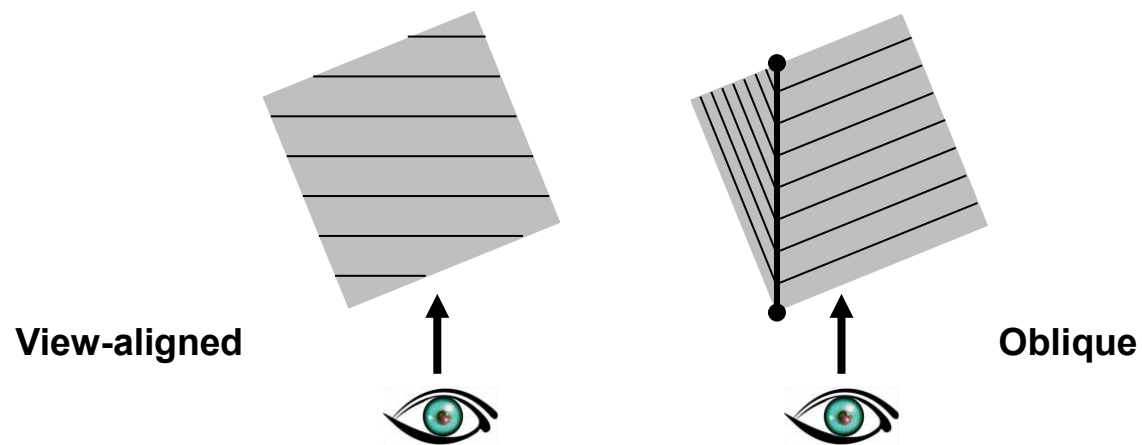
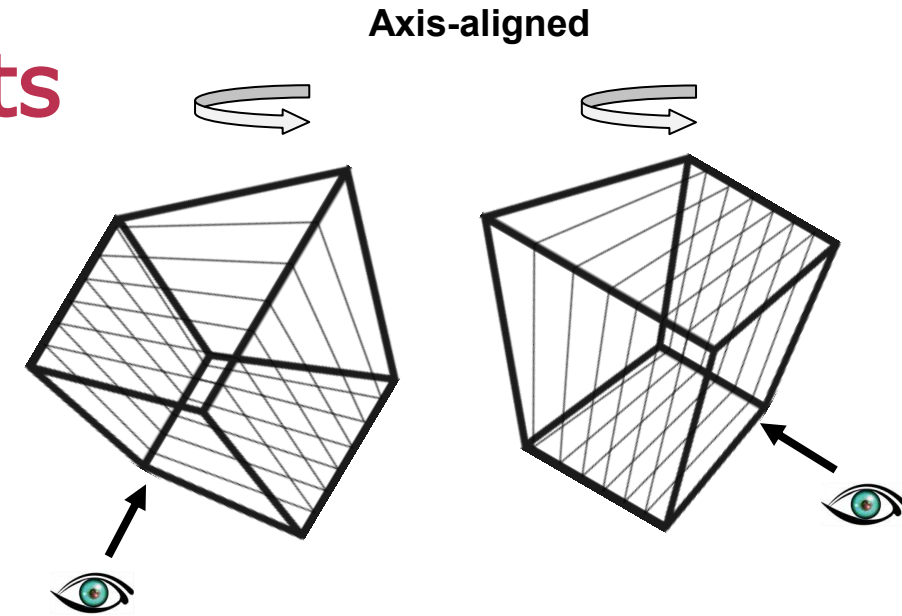
- **Pure mobile rendering**
 - Move all the work to the mobile
 - Nowadays feasible
- **Direct Volume Rendering on mobile. Algorithms**
 - Slices
 - 2D texture arrays
 - 3D textures

Rendering Volumetric Datasets

- **Slices**

- Typical old days volume rendering
 - Several quality limitations
 - Subsampling & view change

- Improvement: Oblique slices [Kruger 2010]

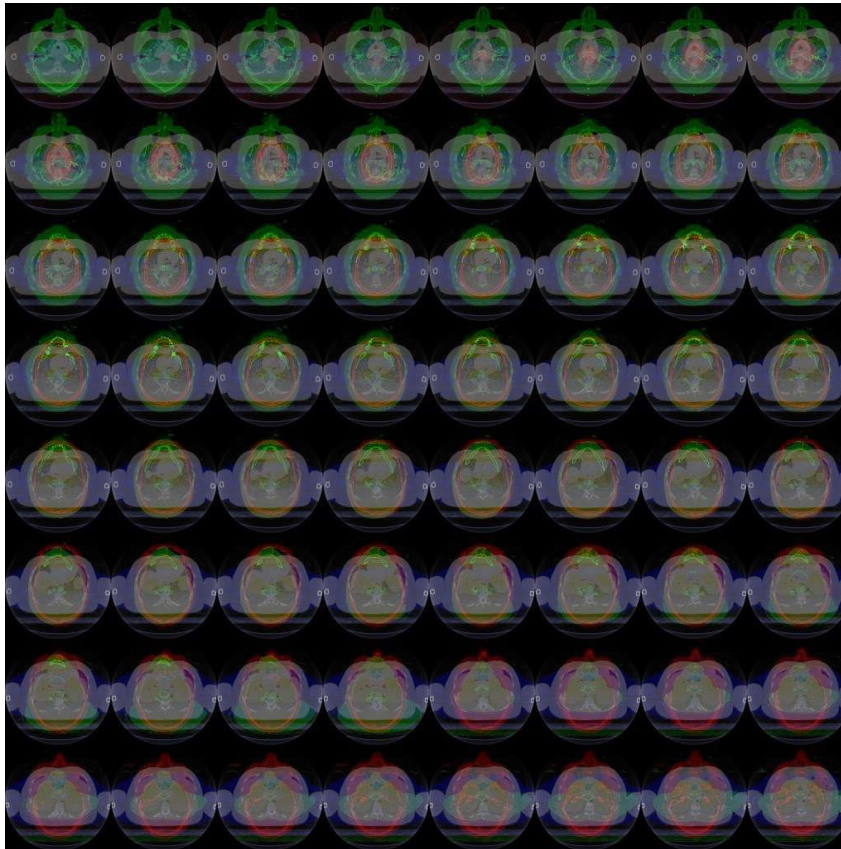


Rendering Volumetric Datasets

- **2D texture arrays + texture atlas [Noguera et al. 2012]**
 - Simulate a 3D texture using an array of 2D textures
 - Implement GPU-based ray casting
 - High quality
 - Relatively large models
 - Costly
 - Cannot use hardware trilinear interpolation

Rendering Volumetric Datasets

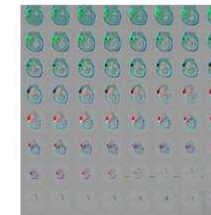
- 2D texture arrays + texture atlas



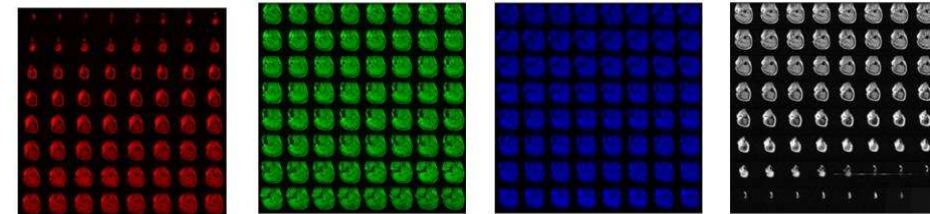
3D texture representation



Texture mosaic representation



Texture mosaic per channel
Illustration



Rendering Volumetric Datasets

- **2D texture arrays + compression [Valencia & Vázquez, 2013]**
 - Increase the supported sizes
 - Increase framerates

Compression format	Compression ratio	RBA format	RGBA format	GPU support	Overall performance	Overall quality
ETC1	4:1	Yes	No	All GPUs	Good (RC)	Good
PVRTC	8:1 and 16:1	Yes	Yes	PowerVR	Not so good	Bad
ATITC	4:1	Yes	Yes	Adreno	Good (RC)	Good

Rendering Volumetric Datasets

- **2D texture arrays + compression**

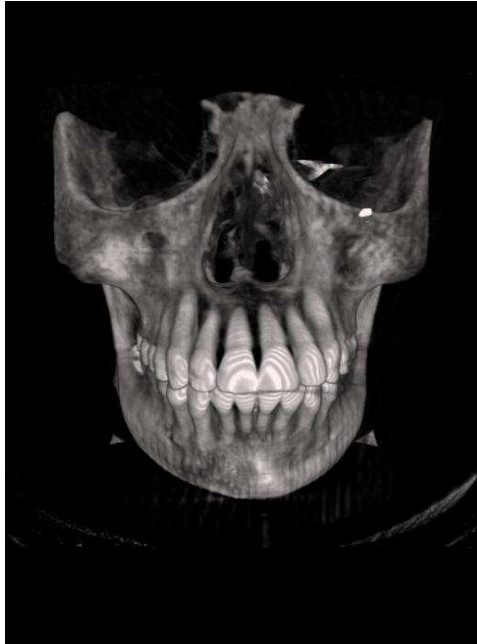
- ATITC: improves performance from 6% to 19%. With an average of 13.1% and a low variance of performance.
- ETC1(-P): improves performance from 6.3% to 69.5%. With an average of 32.6% and the highest variance of performance.
- PVRTC-4BPP: improves performance from 4.7% and 36.% and PVRTC-2BPP: from 9,5% to 36,5%. The average performance of both methods is ~15% with high variance.

Rendering Volumetric Datasets

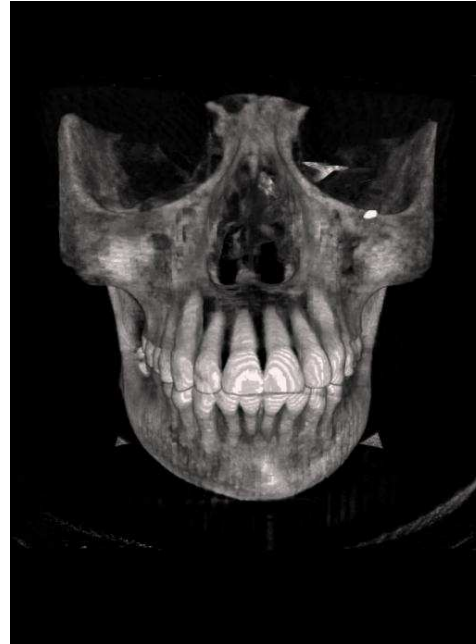
- **2D texture arrays + compression**
 - Ray-casting: gain performance in average of 33%.
 - Slice-based: gain performance in average of 8%.
 - Ray-casting frame rates are better in all cases compared to slice-based.

Rendering Volumetric Datasets

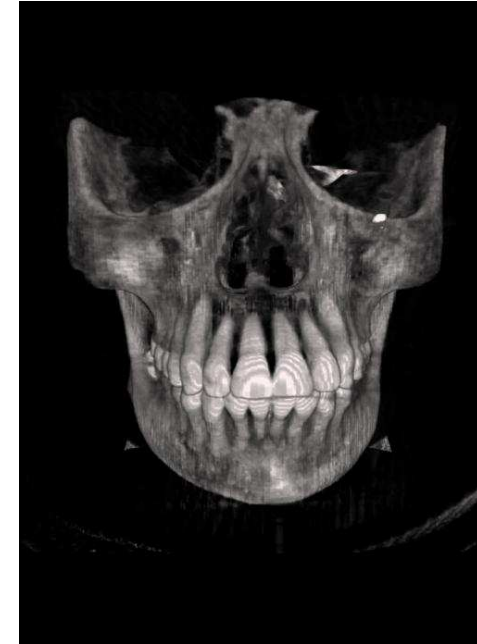
- 2D texture arrays + compression



Uncompressed



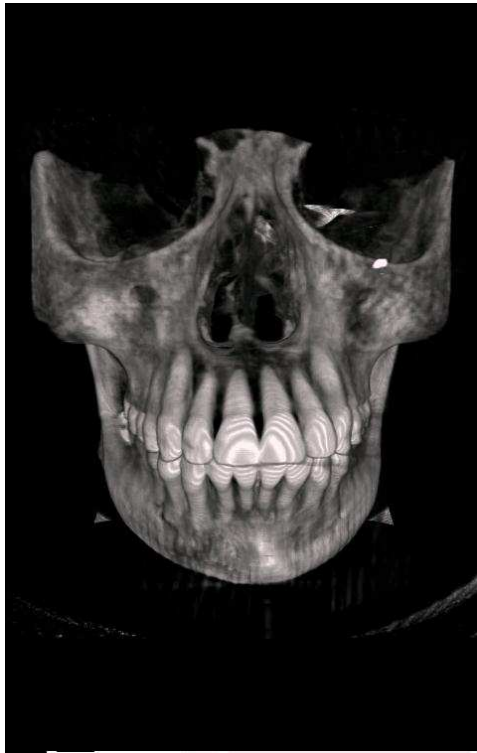
Compressed with ATI-I



Compressed with ETC1-P

Rendering Volumetric Datasets

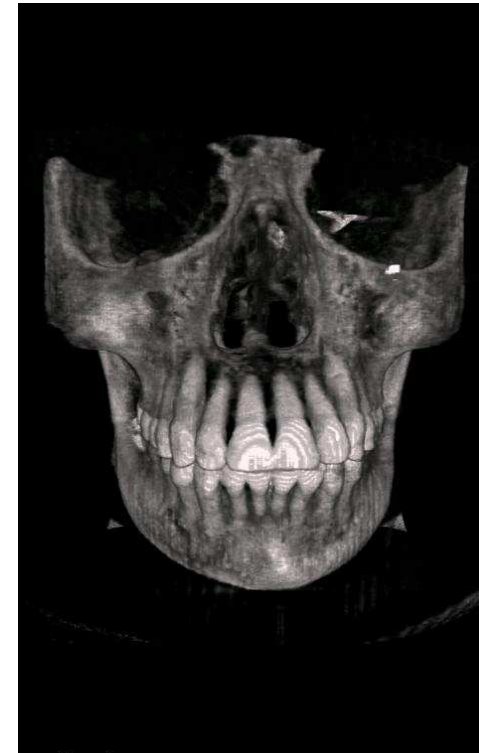
- 2D texture arrays + compression



Uncompressed



Compressed with PVRTC-4BPP

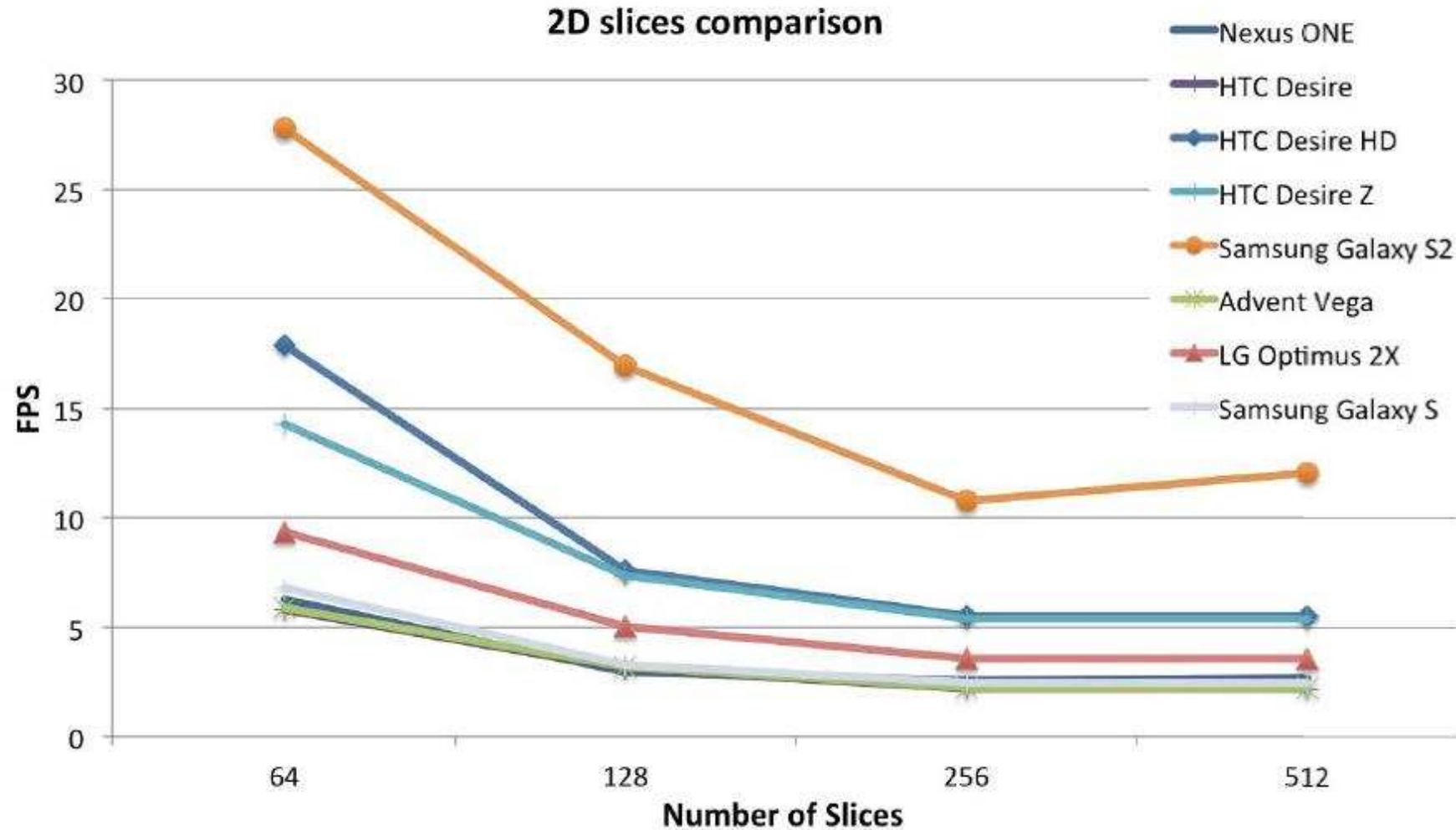


Compressed with PVRTC-2BPP

Rendering Volumetric Datasets

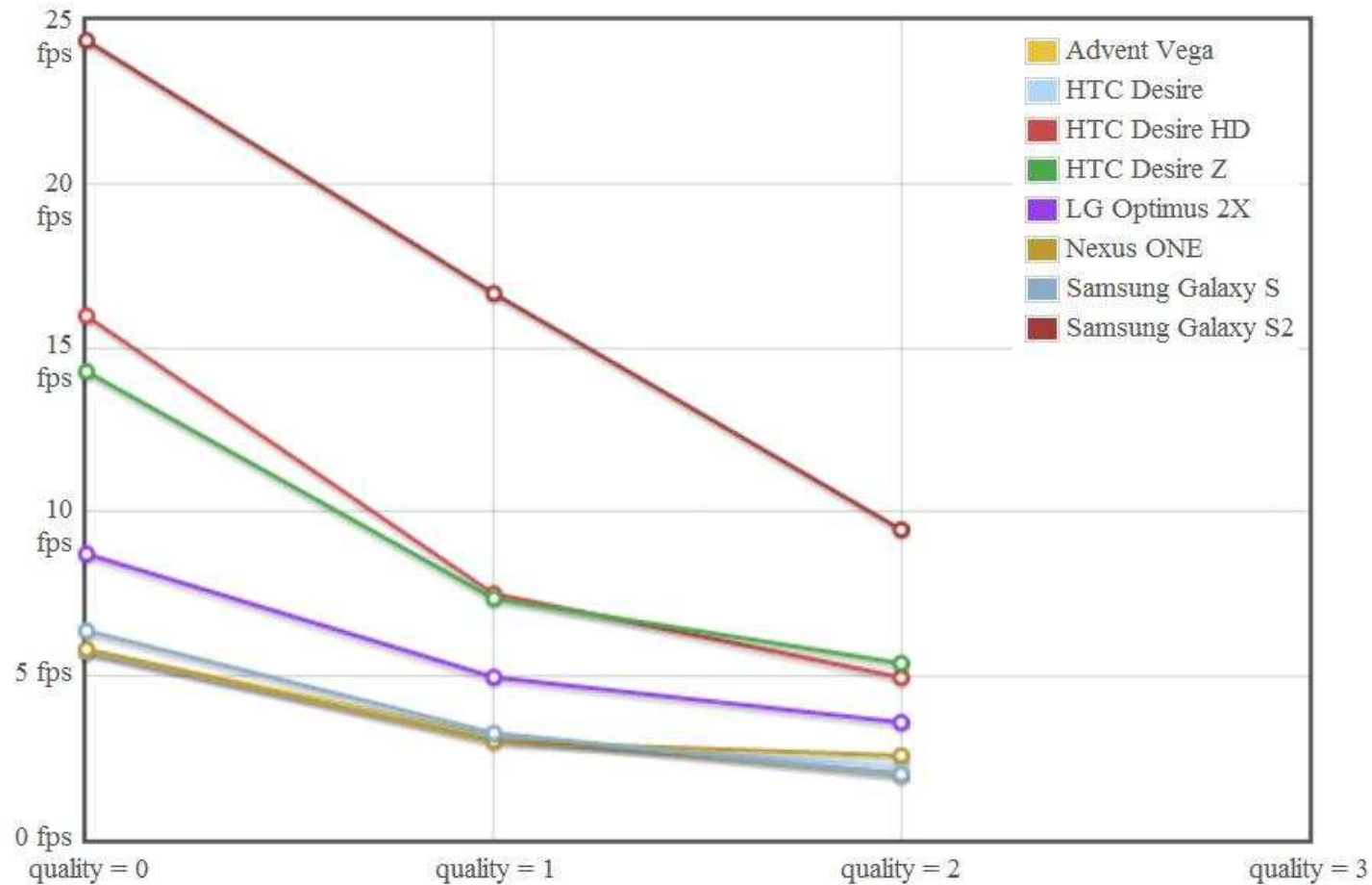
- **3D textures [Balsa & Vázquez, 2012]**
 - Allow either 3D slices or GPU-based ray casting
 - Initially, only a bunch of GPUs sporting 3D textures (Qualcomm's Adreno series ≥ 200)
 - Performance limitations (data: 256^3 – screen resol. 480x800)
 - 1.63 for 3D slices
 - 0.77 fps for ray casting

Rendering Volumetric Datasets



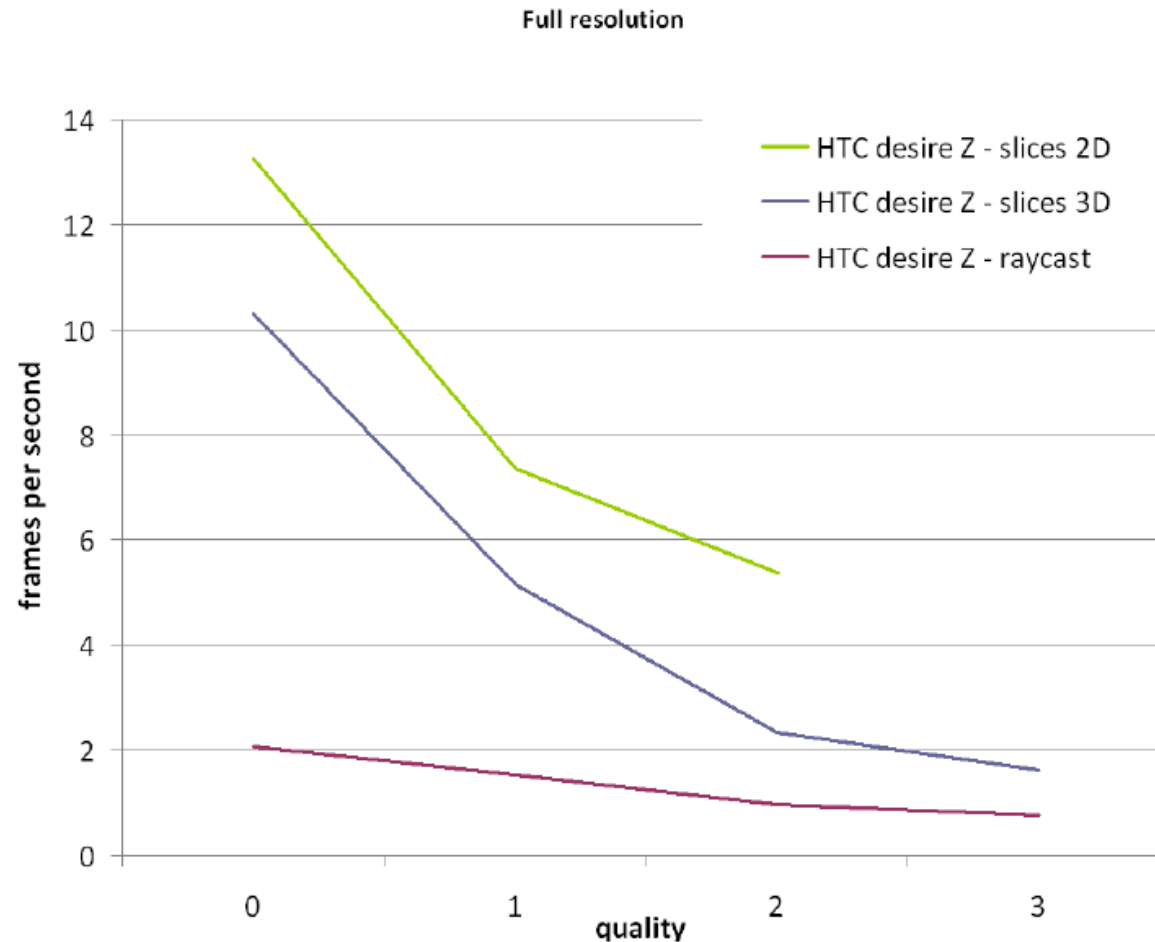
Rendering Volumetric Datasets

- 2D slices



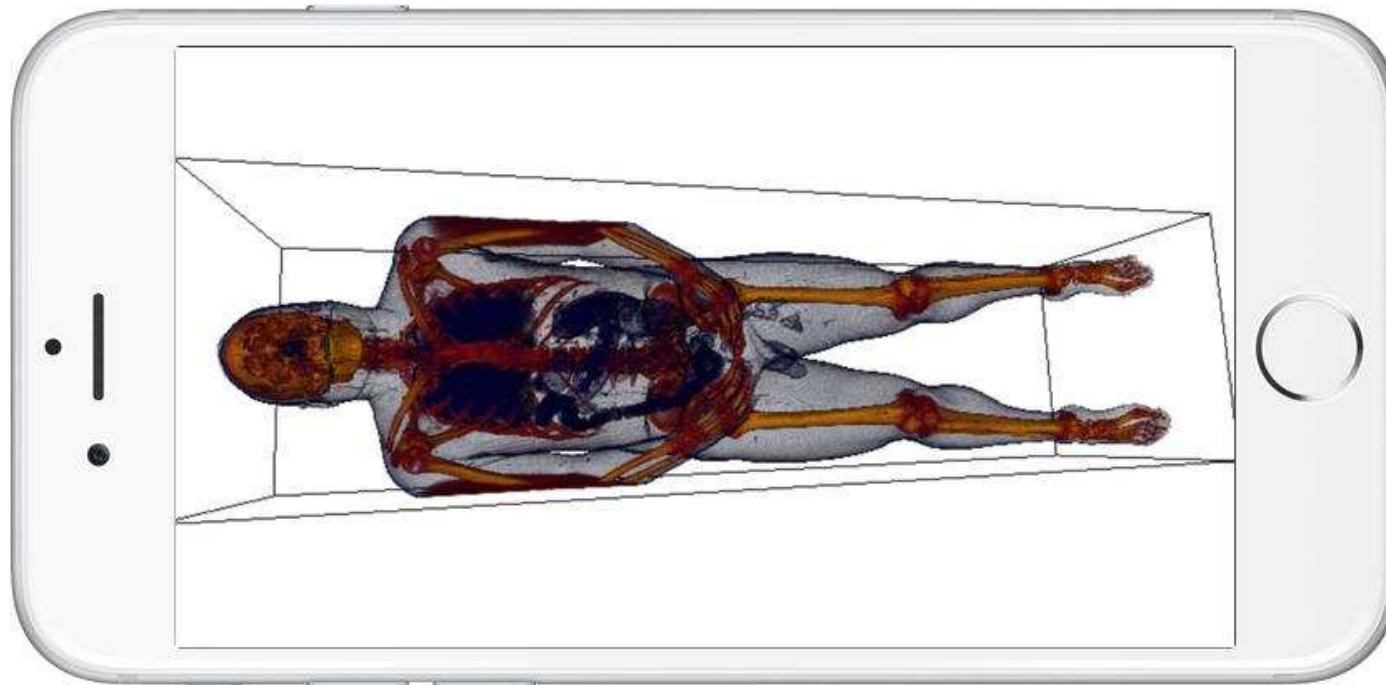
Rendering Volumetric Datasets

- 2D slices vs 3D slices vs raycasting



Rendering Volumetric Datasets

- Using Metal on an iOS device [Schiewe et al., 2015]



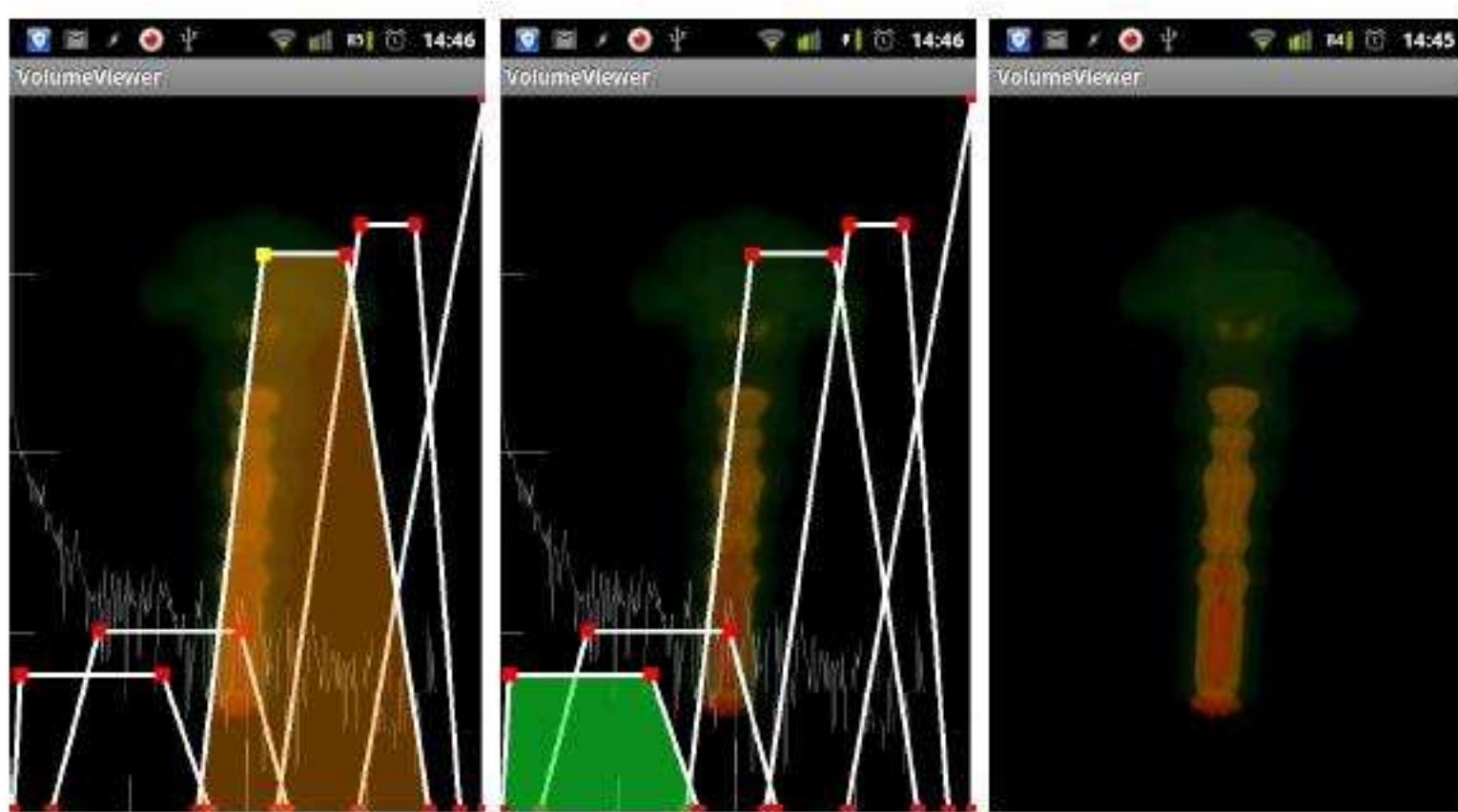
Taken from [Schiewe et al., 2015]

Volume data. GPU ray casting on mobile

- **Using Metal on an iOS device [Schiewe et al., 2015]**
 - Standard GPU-based ray casting
 - Provides low level control
 - Improved framerate (2x, to a maximum of 5-7 fps) over slice-based rendering
 - Models noticeably smaller than available memory (max. size was $256^2 \times 942$)

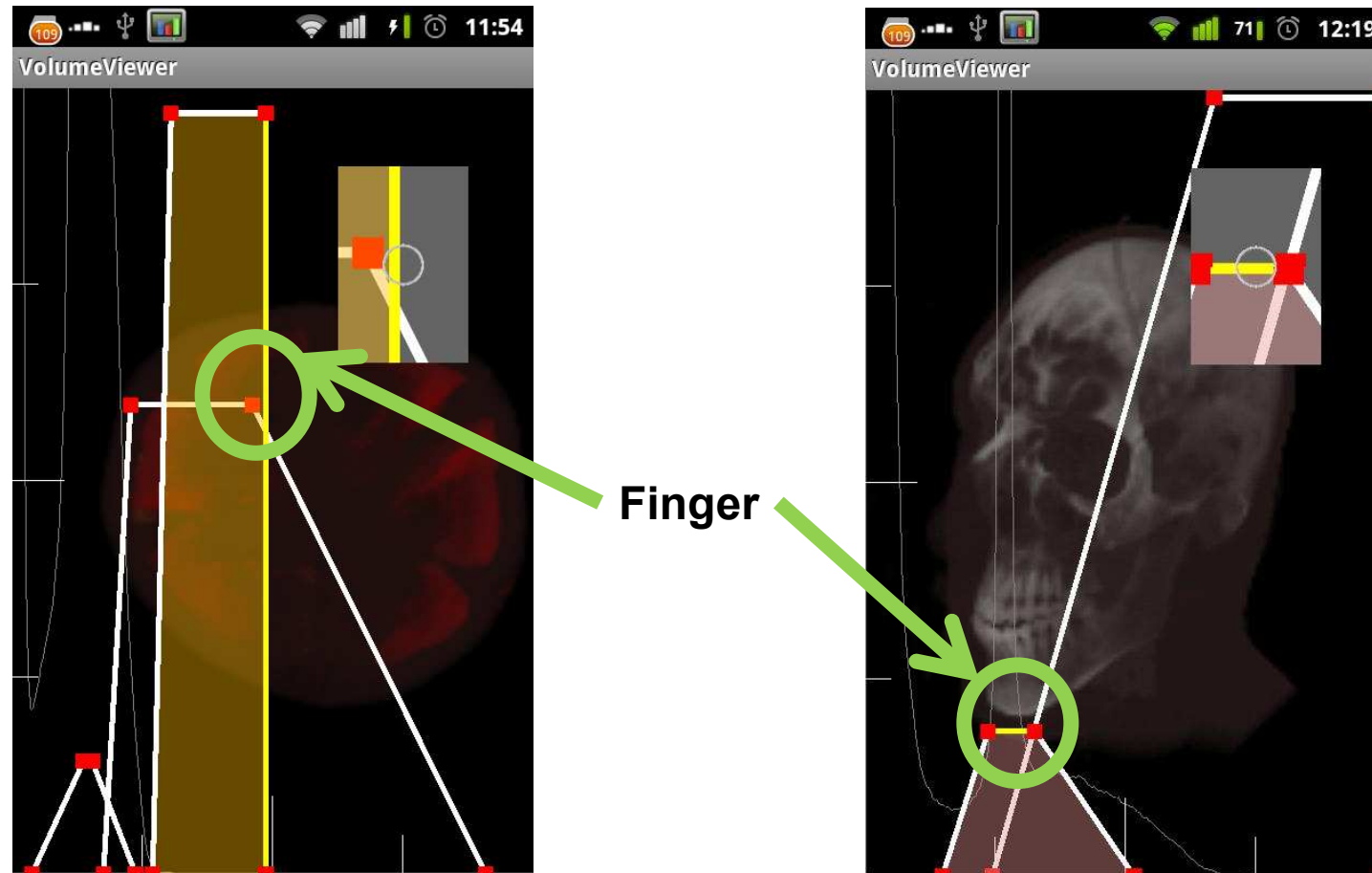
Rendering Volumetric Datasets

- Challenges: Transfer Function edition



Rendering Volumetric Datasets

- Challenges: Transfer Function edition



Rendering Volumetric Datasets

- **Conclusion**

- Volume rendering on mobile devices possible but limited
 - Can use daptive rendering (half resolution when interacting)
- 3D textures in core GLES 3.0
 - Still limited performance (~7fps...)
- Interaction still difficult
- Client-server architecture still alive
 - Can overcome data privacy/safety & storage issues
 - Better 4G-5G connections
 - ...

Next Session

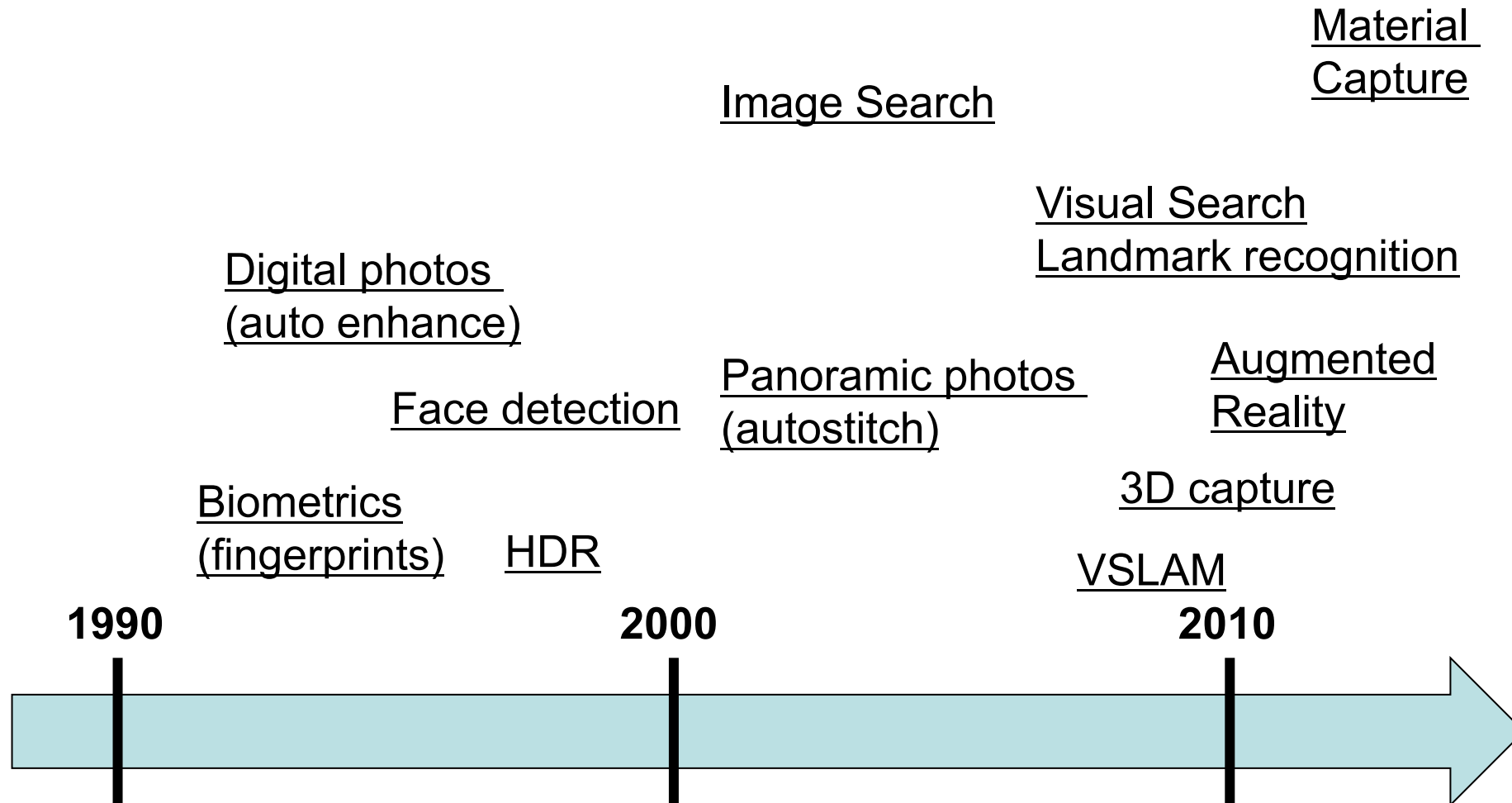
MOBILE METRIC CAPTURE AND RECONSTRUCTION

Part 5.1

Mobile Metric Capture & Reconstruction: Introduction

Enrico Gobbetti, CRS4

Computer vision and mobile applications



Computer vision and mobile applications

- **Mostly 2D**

- Image enhancement
- Image stitching
- Image matching
- Object detection
- Texture classification
- Activity recognition
- ...

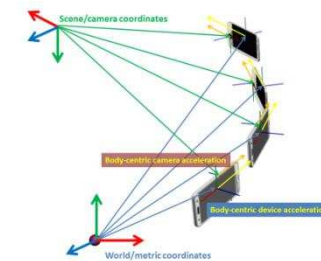
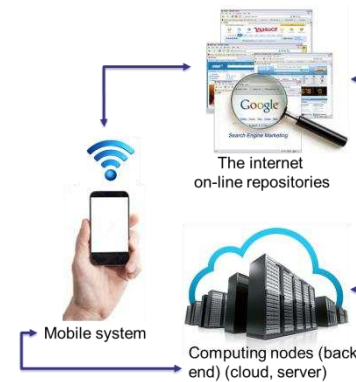
- **Mostly 3D**

- Camera localization
- Pose estimation
- 3D shape recovery
- 3D scene reconstruction
- Material/appearance recovery
- Augmented reality
- ...

Applications made possible by specific features of mobile devices!

- **Features**

1. Mobility
2. Camera
3. Active light
4. Non-visual sensors
5. Processing power
6. Connectivity
7. Display



Features (1/7): Mobility

- **Consumer**
 - Smartphones
 - Tablets
- **Embedded**
 - Autonomous driving
 - Assistive technologies
- **Specific**
 - Drones
 - Robots



Features (1/7): Mobility

- **Consumer**

- Smartphones
- Tablets

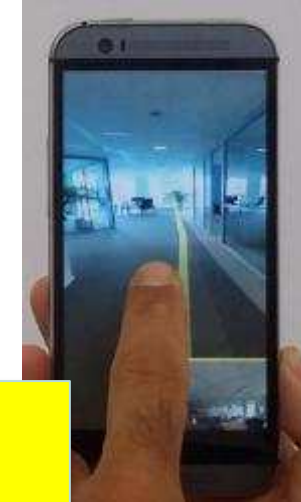
- **Embedded**

- Autonomous driving
- Assistive technology

On-site applications / Personal applications / Motion and/or location taken into account / Embedded solutions

- **Specific**

- Drones
- Robots



Features (2/7): High-res/flexible camera

- **Common features**
 - High resolution and good color range (>12 MP, HDR)
 - Small sensors (similar to point and shoot cameras – approx. 1/3")
 - High video resolution and frame rate (4K at 30fps)
- **Wide variety of field of views**
 - standard, fisheye, spherical
- **Specialized embedded cameras...**
 - Better lenses and sensors...



Features (2/7): High-res/flexible camera

- **Common features**

- High resolution and good color range (>12 MP, HDR)
- Small sensors (similar to point and shoot cameras – approx. 1/3")
- High video resolution and frame rate (4K at 30fps)

- **Wide variety of**

- standard, fisheye

- **Specialized em**

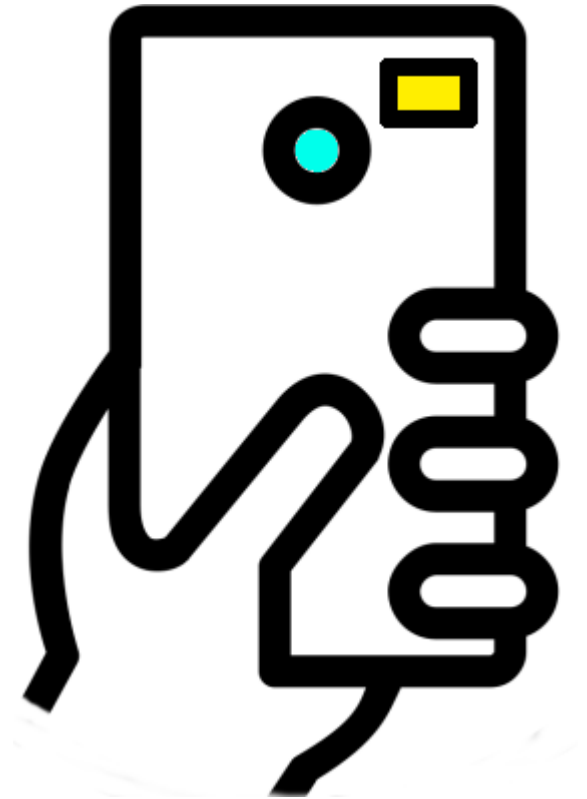
- Better lenses and sensors...

Visual channel is the primary one
Computational photography
Apps analyze/use snapshots or videos



Features (3/7): Active lighting

- **All smartphones have a flashlight**
 - LED source at fixed distance from camera
- **Custom devices have integrated emitters**
 - Google TANGO / Microsoft Kinect
 - Integrated depth sensor
- **Leads to specialized capture procedures**



Features (3/7): Active lighting

- All smartphones have a flashlight

- LED source at fixed position

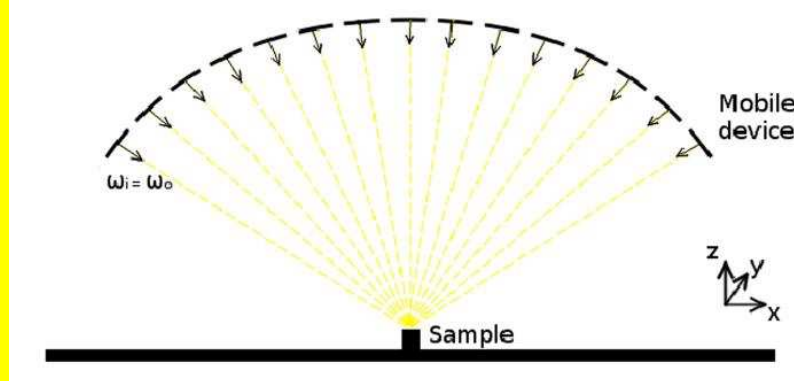
- Custom devices with specialized emitters

- Google TANGO / Microsoft Kinect
 - Integrated depth sensors

- Leads to specialized capture procedures

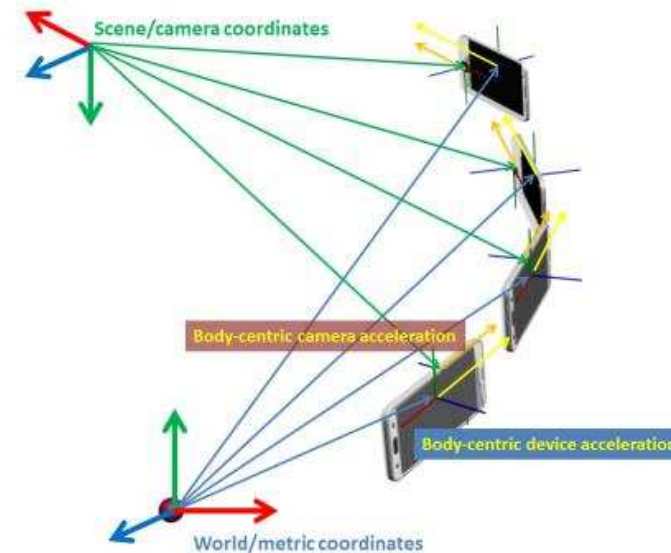
Specialized capture procedures exploiting synchronization of illumination and visual sensing

Ex. Riviere et al. **Mobile surface reflectometry**. *Computer Graphics Forum*. 2015.



Features (4/7): Non-visual sensors

- **Absolute reference**
 - GPS / A-GPS
 - Mainly for outdoor applications
 - Magnetometer
 - Enable compass implementation
 - Often inaccurate for indoor
- **Relative reference**
 - Accelerometer
 - Variable accuracy (sensitive to temperature)
 - Good metric information for small scale scene
 - Gyroscope
 - Very good accuracy for device relative orientation
- **Synced with camera!**



Features (4/7): Non-visual sensors

- **Absolute reference**

- GPS / A-GPS
 - Mainly for outdoor
- Magnetometer
 - Enable compass
 - Often inaccurate

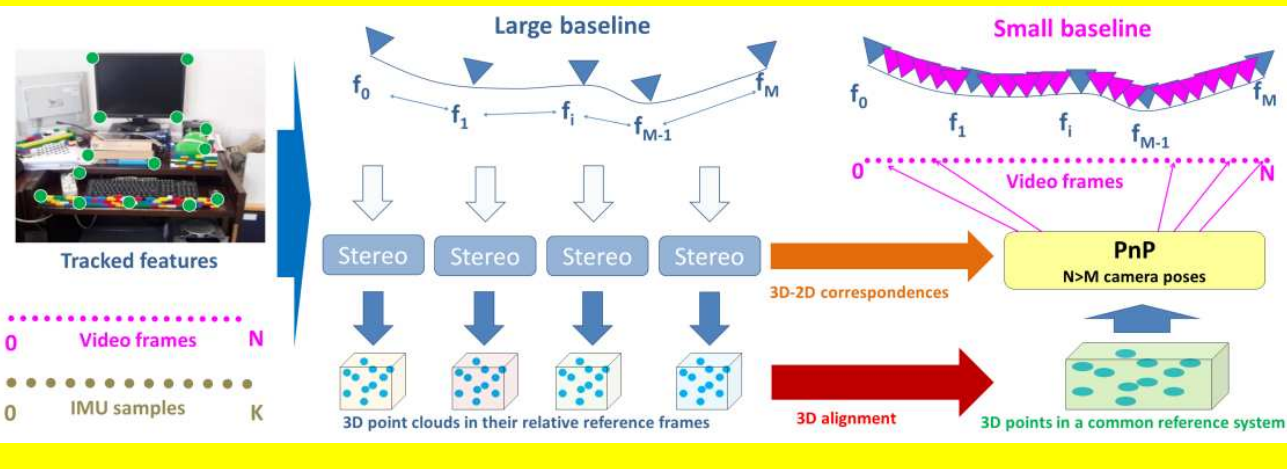
- **Relative reference**

- Accelerometer
 - Variable accuracy
 - Good metric in
- Gyroscope
 - Very good accuracy for device relative orientation

- **Synced with camera!**

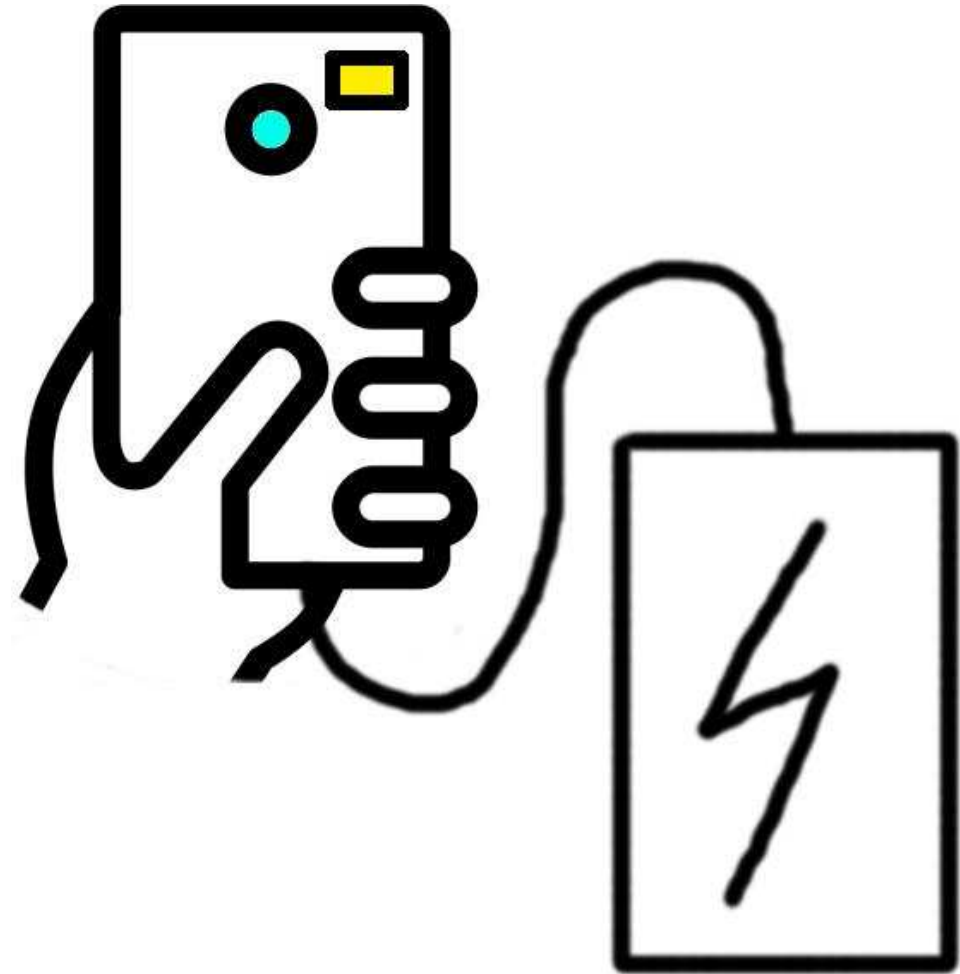
Data fusion!

Ex. Garro et al. **Fast Metric Acquisition with Mobile Devices**. VMV 2016



Features (5/7): Processing power

- **Growing performance of mobile CPU+GPU**
 - (see previous sections)
- **Capable to execute computer vision pipeline on mobile device**
 - i.e. OpenCV for Android
- **Some limitations due to power consumption**

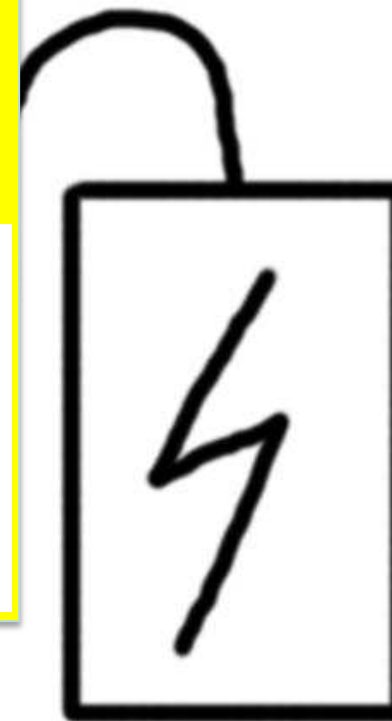


Features (5/7): Processing power

- **Growing performance**
CPU+GPU
 - (see previous section)
- **Capable to execute**
vision pipeline
 - i.e. OpenCV for Android
- **Some limitations**
consumption

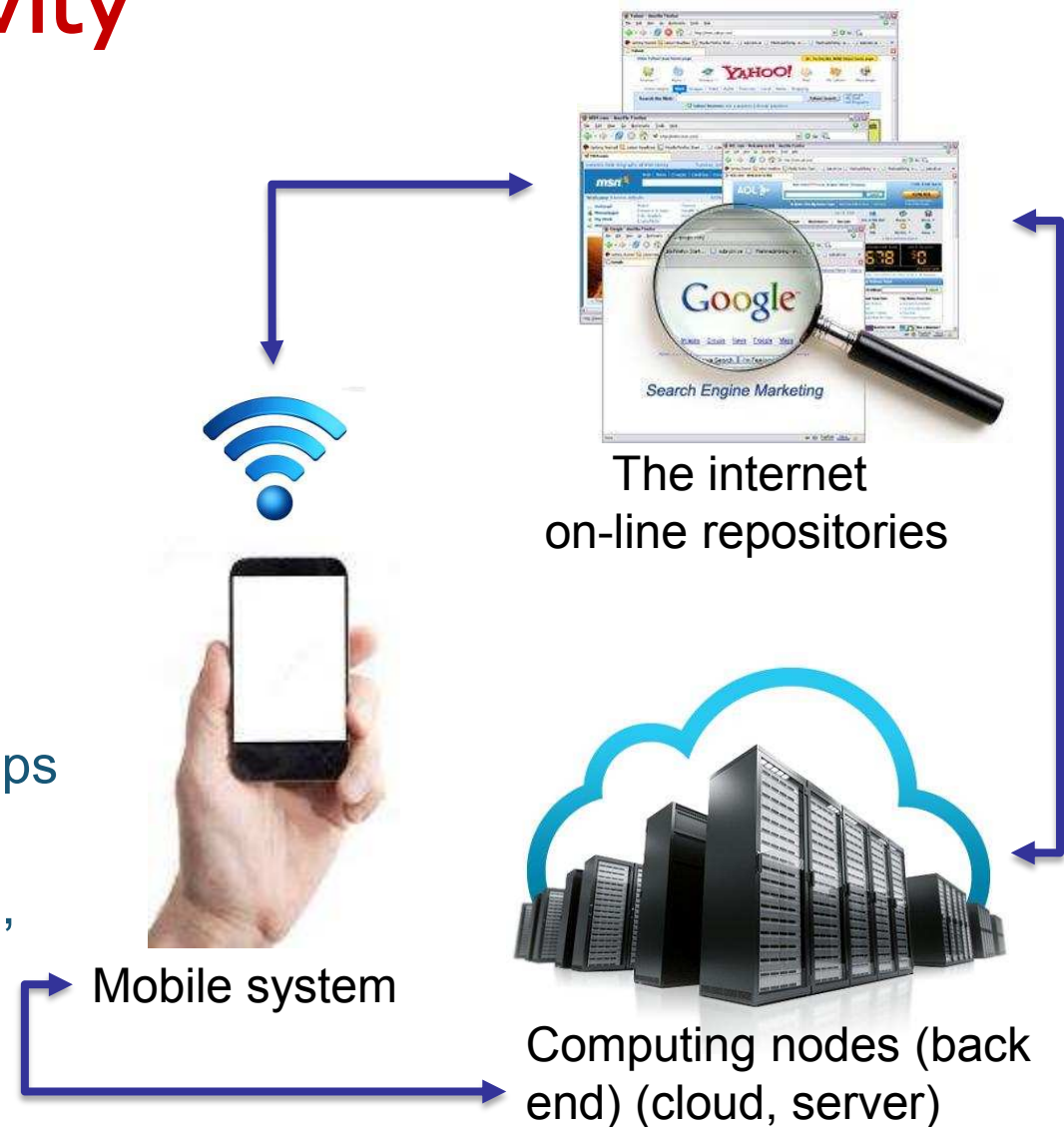
On-board pre-processing or even full processing

Ex. Tanskanen et al. **Live Metric 3D Reconstruction on Mobile Phones**. ICCV2013



Features (6/7): Connectivity

- **Many connectivity options**
 - Local area: NFC, Bluetooth, Bluetooth Low Energy, Wi-Fi 802.11x
 - Wide area: Cellular wireless networks: 3G/4G/5G
- **Mobile devices can connect at local or wide area at reasonable speed**
 - Typical LTE/4G: 18 Mbps down, 9.0 Mbps up
 - Typical Wi-Fi: 54Mbps (g), 300Mbps (n), 1Gbps (ac).
- **Lo-cost -> No-Costs**

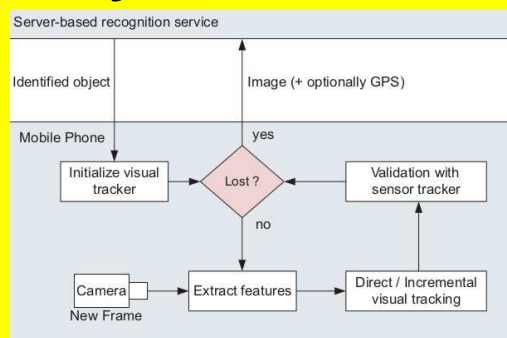


Features (6/7): Connectivity

- **Many connectivity options**
 - Local area: NFC, Low Energy, Wi-Fi
 - Wide area: Cellular 3G/4G/5G
- **Mobile devices connect to local or wide area networks at high speed**
 - Typical LTE/4G: up to 100Mbps
 - Typical Wi-Fi: 54Mbps (802.11g) to 1Gbps (ac).
- **Lo-cost -> No-Costs**

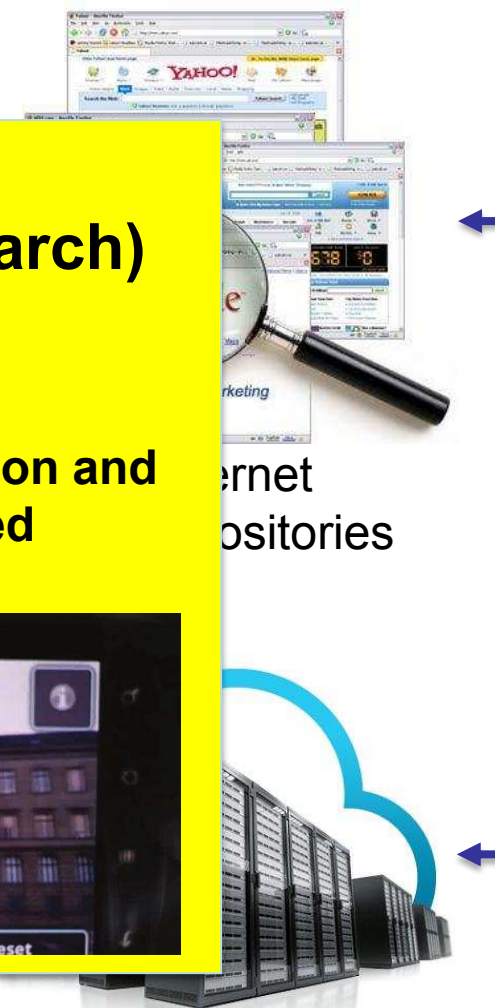
Load balancing (client / server)
Access to large databases (e.g., search engines)
Communication

Ex. Gammeter et al. **Server-side object recognition and client-side object tracking for mobile augmented reality.** CVPRW 2010.



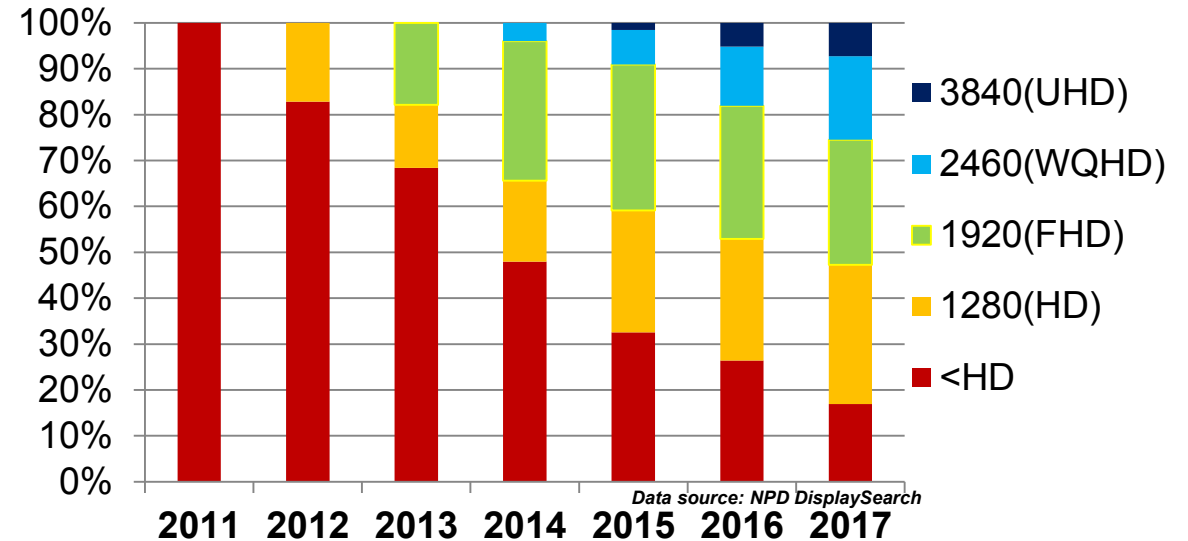
Mobile system

Computing nodes (back end) (cloud, server)



Features (7/7): Display!

- **Hi-res/hi-density display**
 - Data presentation!
 - Large with respect to processing power
- **Co-located with camera + other sensors**
 - Tracking during capture!
- **Touch screen**
 - Co-located user-interface
 - Small with respect to fingers (precision, occlusions!)
 - (UI also may exploits other sensors)



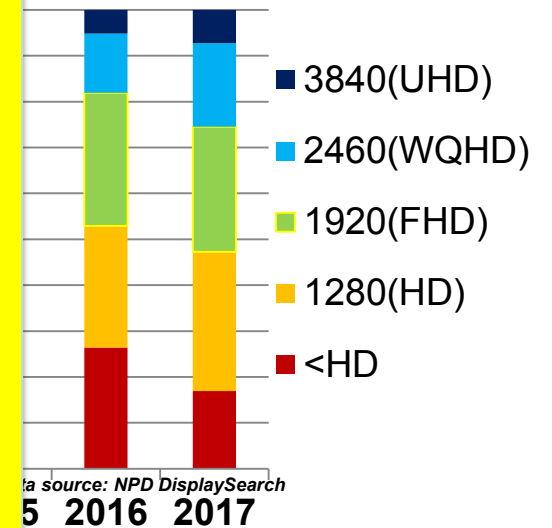
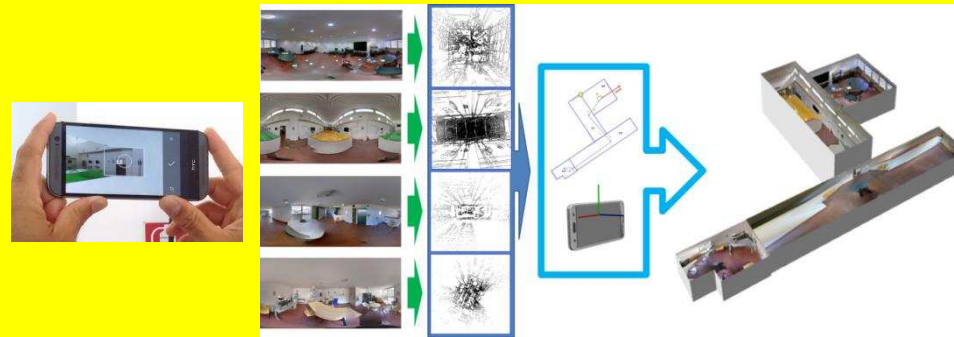
Features (7/7): Display!

- **Hi-res/hi-density**
 - Data presentation
 - Large with respect to
- **Co-located with sensors**
 - Tracking during capture
- **Touch screen**
 - Co-located user-interface
 - Small with respect to occlusions!
 - (UI also may exploit

Data/result presentation

Guided capture / Augmentation

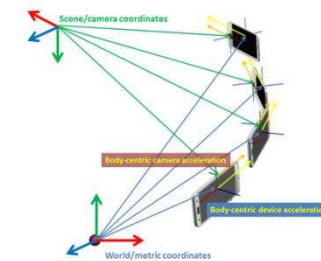
Ex. Pintore et al. **Mobile Mapping and Visualization of Indoor Structures to Simplify Scene Understanding and Location Awareness**. ECCV ACVR 2016



Wrap-up: mobile apps characterized by the exploitation of mobile device features

• Features

1. Mobility
2. Camera
3. Active light
4. Non-visual sensors
5. Processing power
6. Connectivity
7. Display



Next session: case studies!

Part 5.2

Mobile Metric Capture & Reconstruction: Case studies in metric capture

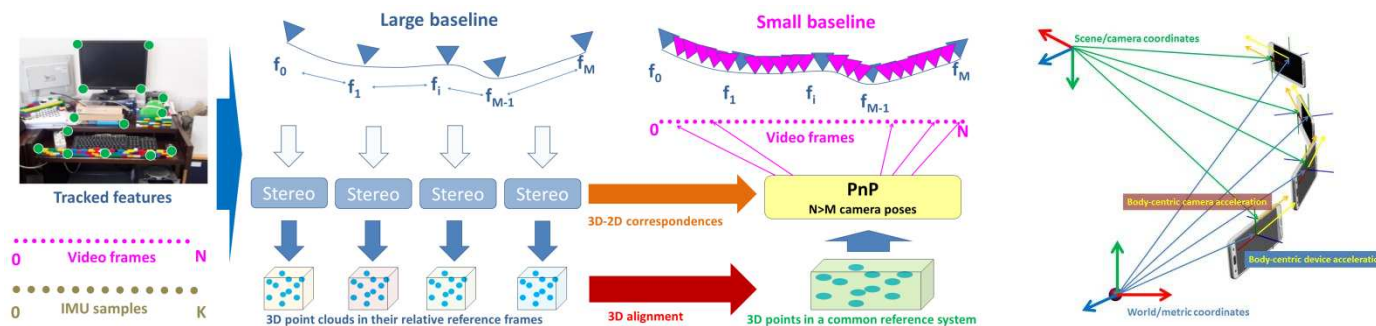
Giovanni Pintore, CRS4

Example 1

DATA FUSION FOR METRIC CAPTURE

Metric acquisition with a commodity mobile phone

- **Goal**
 - Capture 3D models with real-world measures
- **Data fusion approach**
 - Exploit synchronization of visual sensor & IMU to capture scenes in real-world units

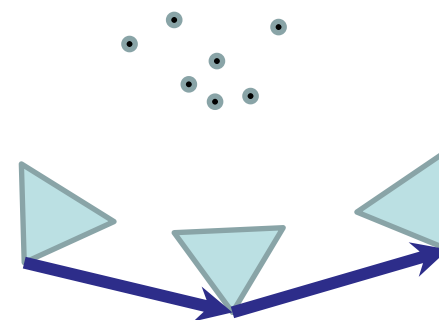


Garro et al. **Fast Metric Acquisition with Mobile Devices**. VMV 2016



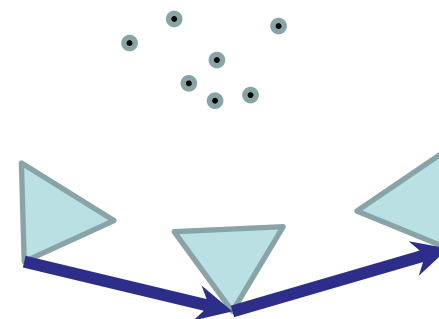
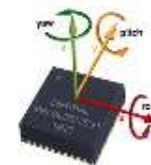
Structure-from-Motion + Dense reconstruction

- **SfM reconstructs a point cloud from a series of images**
 - 3D positions of (sparse) matched features
 - Camera positions and orientations
- **Many approaches for densification**
 - Pipeline showed to work at interactive rates on phones (Taskanen et al 2013)
- **SCALE AMBIGUITY**



Data fusion: Visual + IMU

- **Use sensors synced with visual channel**
 - GPS+Magnetometer generally not applicable
 - IMU returns orientation and acceleration in real world units
- **Idea**
 - track camera movement with IMU during visual capture
 - use IMU data to find out the real-world distance between SfM camera positions, resolving the scale ambiguity



Data fusion: Visual + IMU

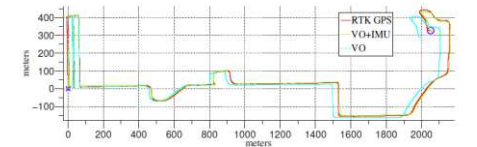
- The accelerometer returns acceleration
- Therefore, we should be able to compute the displacement between two camera positions as

$$x(T1, T2) = \left\| \int_{T1}^{T2} \left(v(T1) + \int_{T1}^{t'} a(t) dt \right) dt' \right\|$$

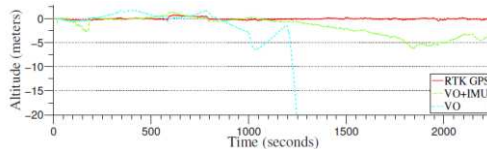
- Not so easy: onboard IMU sensors are biased and noisy and SfM camera positions are sparse

Data fusion approaches (1/4)

- Match position from IMU integration with position from SfM, coping with noise/bias by extensive filtering



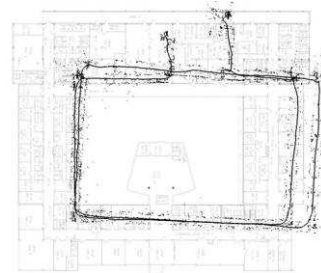
(b) Trajectory comparison (top view)



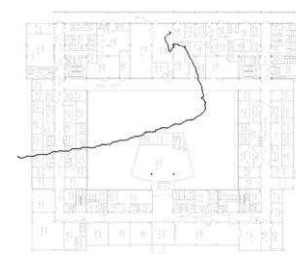
(c) Altitude comparison

A new approach to vision-aided inertial navigation [Tardif et al 2010]

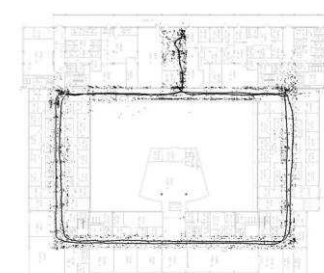
Vision only



IMU only



Vision+IMU



Visual-Inertial Navigation, Mapping and Localization:
A Scalable Real-Time Causal Approach [Jones, Soatto 2011]

- Requires **LONG** acquisition times and **LONG** offline processing times

Data fusion approaches (2/4)

- **Ad-hoc online solutions taking into account IMU characteristics**
 - Segment motion in “swift movements” with large accelerations
 - Integration of IMU acceleration to derive position matched with SfM
 - Continuous process of outlier rejection and re-estimation of scale

Live metric 3D reconstruction on
Mobile Phones [Tanskanen et al. 2013]



$$\arg \min_{\lambda} = \sum_{i \in I} \|\vec{x}_i - \lambda \vec{y}_i\|^2$$

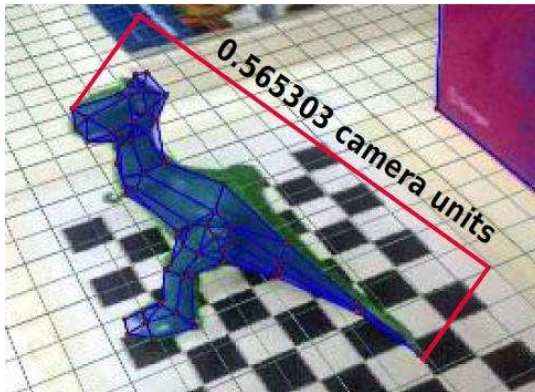
One estimate of λ at the end of each swift movement
Estimation of scale λ only on inlier set I

- **Working but motion-dependent and prone to accumulation error due to integration**

Data fusion approaches (3/4)

- Match accelerations from IMU with accelerations from SfM at SfM frame-rate (large baseline!)
 - Downsample and anti-alias IMU samples at SfM frame rate
 - Optimize scale and bias

Hand-waving away scale [Ham et al. 2014]



$$\arg \min_{s, \mathbf{b}} \eta \{ s \cdot \hat{\mathbf{A}}_V + \mathbf{1} \otimes \mathbf{b}^\top - \mathbf{D} \mathbf{A}_I \mathbf{R}_I \}$$

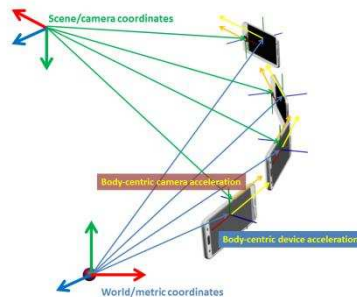
D: convolutional matrix for
antialiasing and downsampling
IMU signal

- Requires very long acquisition times due to downsampling at SfM rate

Data fusion approaches (4/4)

- **Match accelerations from IMU with accelerations from SfM at IMU frame-rate (small baseline!)**
 - **Upsample** SfM samples at high rate using all available visual data
 - Estimate acceleration from upsampled transforms and match them to IMU samples using robust fitting

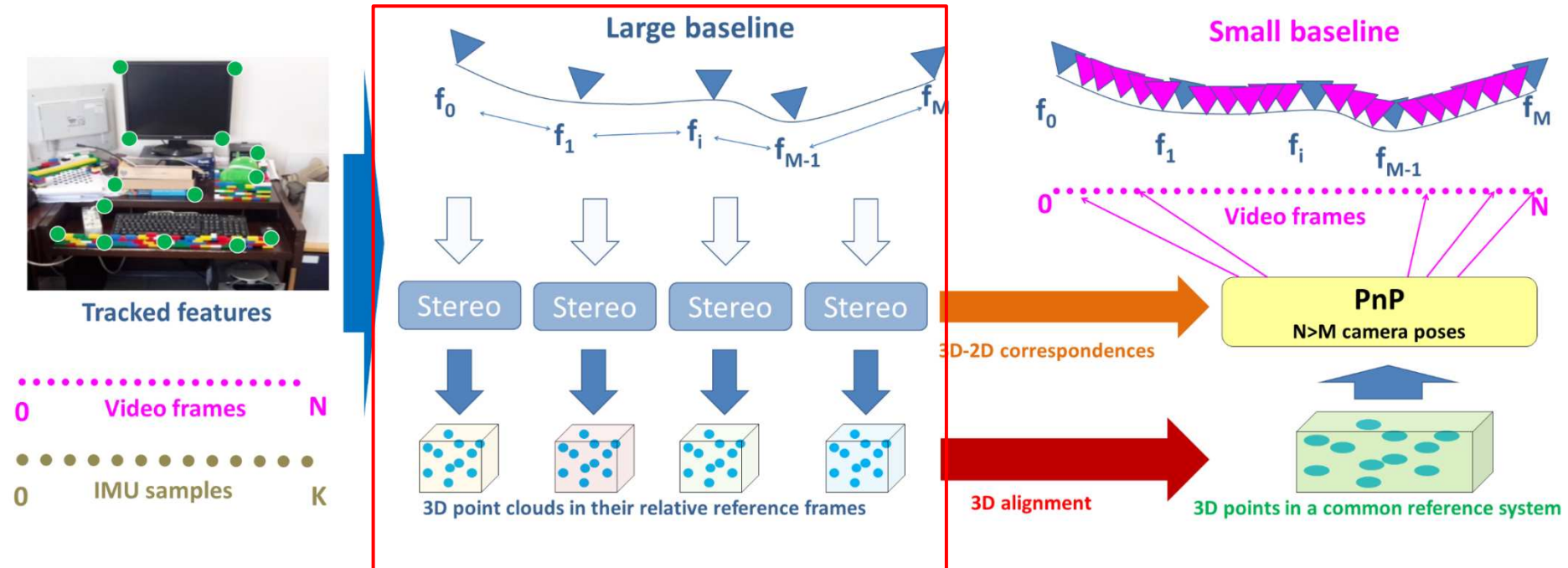
Fast Metric Acquisition with Mobile Devices. [Garro et al. 2016]



$$\underset{s,R}{\operatorname{argmin}}\{\|A_c - sRA_s\|\}$$

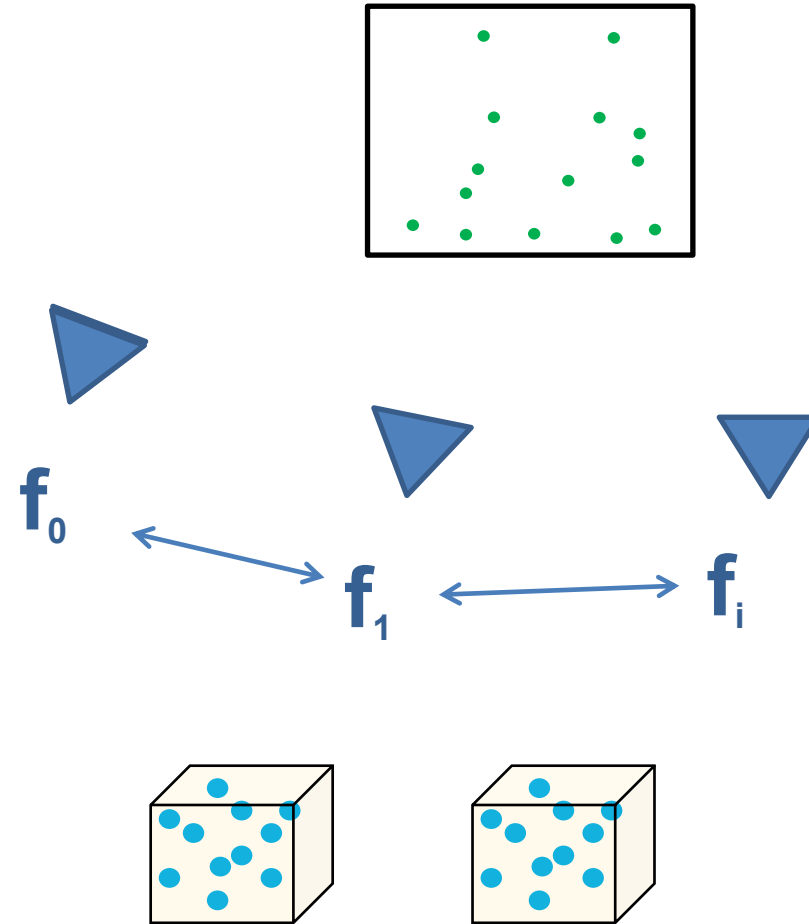
- **Fast, coping with large errors and noise**

Vision Module Pipeline



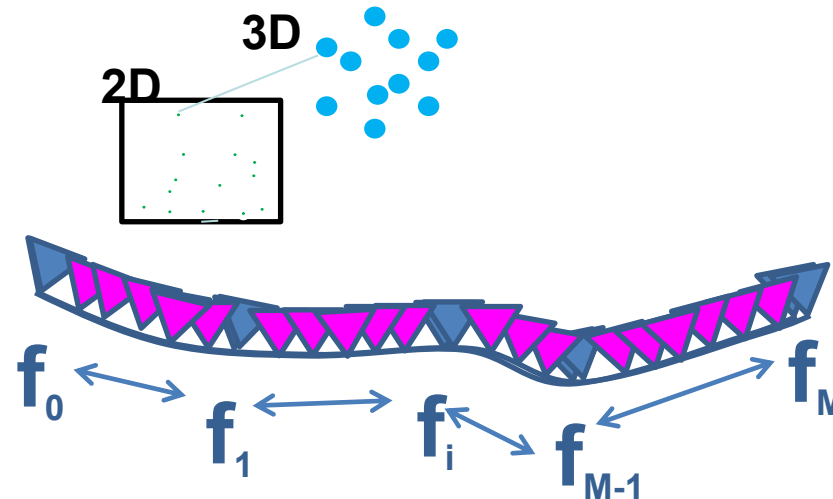
Vision Module

- **Traces Shi-Thomasi features**
- **When baseline is large enough**
 - Estimate Essential Matrix, that is, relative camera pose between f_0 and f_i
 - Calculate a 3D point for each feature point
- **Note: each pair of cameras has its own reference system**



Vision Module

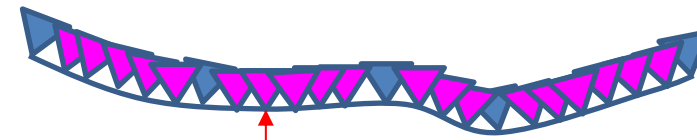
- **Global registration**
 - M point clouds
 - A subset of features is present in each point cloud
 - Use feature correspondence to align all the point cloud in the same reference system
- **Cameras upsampling**
 - Features are tracked for **all** frames
 - Use aligned point cloud and tracking position to estimate cameras for all frames with Perspective-n-Point (**PnP**)



Recovering the scale factor (1/2)

IMU accelerations

$$A_s = \begin{pmatrix} a_s^x(t_0) & a_s^y(t_0) & a_s^z(t_0) \\ \cdot & \cdot & \cdot \\ a_s^x(t_K) & a_s^y(t_K) & a_s^z(t_K) \end{pmatrix}$$



$$p_c''(t_k) = \frac{\sum_{i=0}^8 (-1)^{(i+1)} \delta_i * p_c(t_{k+i-4})}{\Delta t^2}$$

Camera accelerations

$$A_c = \begin{pmatrix} p_c''(t_0)^T R_c(t_0) \\ \cdot \\ p_c''(t_K)^T R_c(t_K) \end{pmatrix}$$

Problem to solve

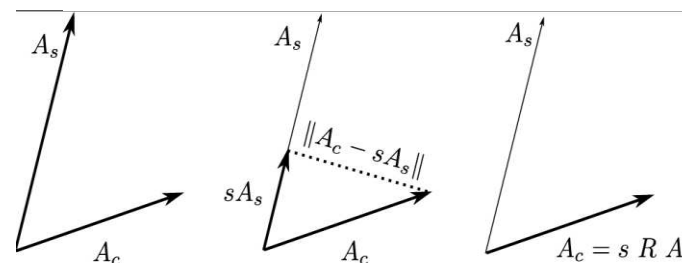
$$\underset{s}{\operatorname{argmin}} \{ \|A_c - sA_s\| \}$$

Recovering the scale factor (2/2)










- **LS, gradient descent (et similia) poorly conditioned**
 - Not so many data
 - Severe outliers
- **Robust fitting use RANSAC approach**
 - Use MLESAC robust estimator to maximize likelihood rather than just the number of inliers
- **Introduce rotation matrix R**
 - Account for orientation bias
 - Improve RANSAC performance

~~$$\underset{s}{\operatorname{argmin}}\{\|A_c - sA_s\|\}$$~~

$$\underset{s,R}{\operatorname{argmin}}\{\|A_c - sRA_s\|\}$$



Results

Scene Name		Real scale m / s.u.	Acquisition info			Our approach		Simple scaling	
			Seconds	Poses	Samples	m / s.u.	Error	m / s.u.	Error
3D printer		2.094	17.0	65	883	2.01	4.0%	2.85	36.1%
Scanner setup		3.565	9.8	53	641	3.45	3.1%	3.12	12.4%
Desktop		6.520	11.3	48	596	6.24	4.2%	5.16	20.8%
Statuettes		2.602	11.5	53	607	2.49	4.5%	2.48	4.9%
Office desk		1.977	30.4	88	471	2.01	1.8%	2.01	1.8%
Office workstation		3.95	12.3	37	1307	3.94	0.3%	3.98	0.6%
Ara pacis		1.568	30.07	77	1569	1.52	2.8%	1.80	13.0%
Workstation (Fastest)		0.707	9.9	34	1305	0.73	2.7%	0.89	20.4%
Desk fast motion		6.918	14.8	74	1718	6.28	9.1%	3.88	44.0%

- **Median error 4% (wrt 10-15% of other STAR solutions)**

Example 2

DATA FUSION AND COMMUNICATION FOR INDOOR CAPTURE

Indoor capture + presentation

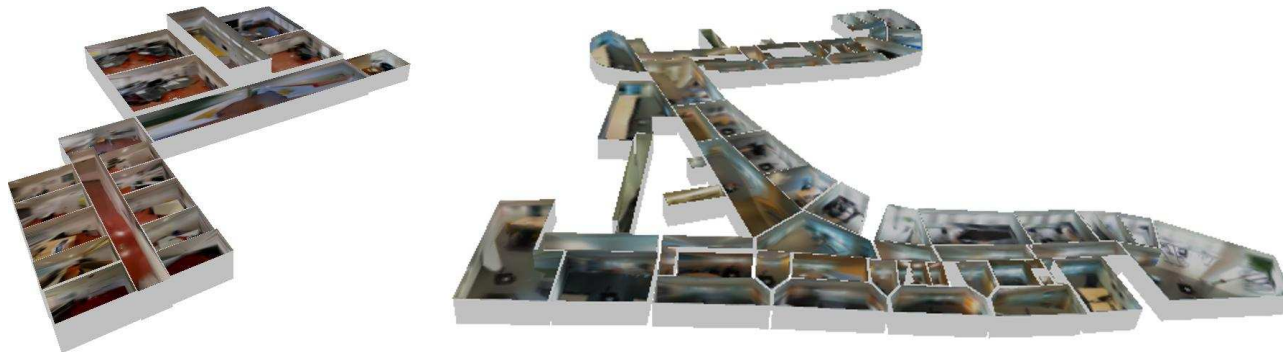
- **Creation and sharing of indoor digital mock-ups**
 - Exploiting the capabilities of modern mobile devices



- **Much interest/applications (security, location awareness, ...)**
 - Need to capture visual information together with room structure

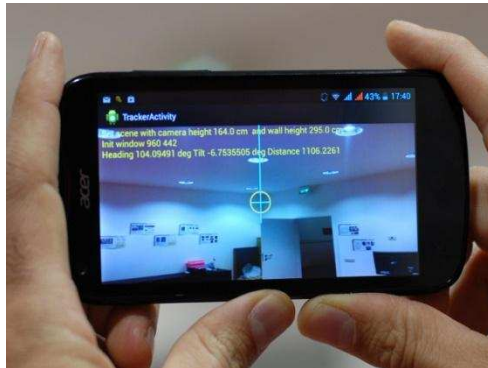
Typical solutions

- **Indoor capture and modeling**
 - Manual modeling
 - Semi-automatic methods based on high-density data
 - **Laser scanning**
 - Professional but expensive, limited to specific applications
 - **Multi-view stereo from photographs**
 - Generally cost effective but hard to apply in the indoor environment
 - » Walls poorly textured, occlusions, clutter
 - » Furthermore: need for heavy MW constraints, computationally demanding

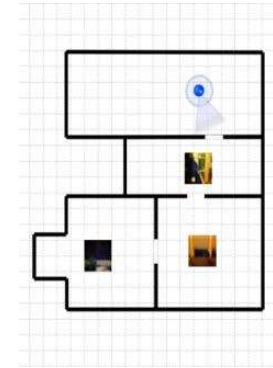


Examples using low-cost mobile devices

- **Interactive capture and mapping of indoor environment**
 - MagicPlan - <http://www.sensopia.com>
 - Floor corners marked via an augmented reality interface
 - Manual editing of the room and floor plan merging using the screen interface
 - Sankar and Seitz: Capturing indoor scenes with smartphones (UIST2012)
 - Corners marked on the screen during video playback



Pintore et al. **Effective mobile mapping of multi-room indoor structures** The Visual Computer, 2014



Sankar et al. **Capturing indoor scenes with smartphones** , UIST2012

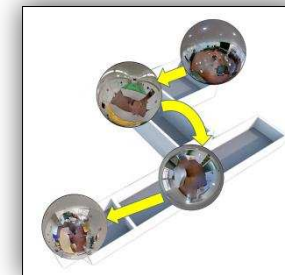
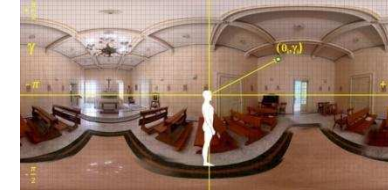
Exploiting panoramic images

- **360 degrees images are easy to capture using common devices**
 - Interactive apps using IMU + GUI + automatic stitching
 - Dedicated cameras
- **360 degrees images are easy to navigate**
 - Spheremaps + emerging formats
 - video+image formats
 - VR devices for immersion
- **What about analyzing them?**



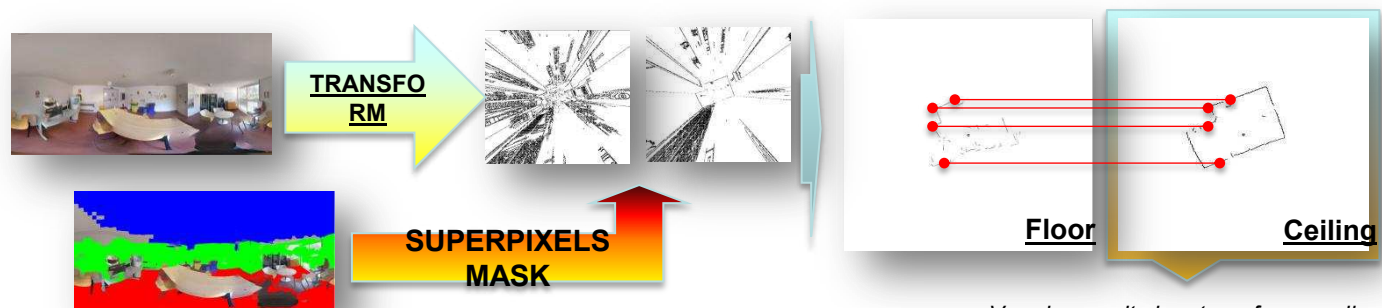
Finding the room structure

- **Take one sphere map per room**
 - Equirectangular images generated by a mobile device
 - Vertical lines aligned with the gravity vector
 - Image approx. oriented towards magnetic North
 - Eventually use IMU + Visual features for stitching
- **Track user motion to identify connections between rooms**
 - Use IMU + Visual Features for tracking
- **Solve local + global optimization to find indoor structure**
 - Multi-room environment



Finding the room structure

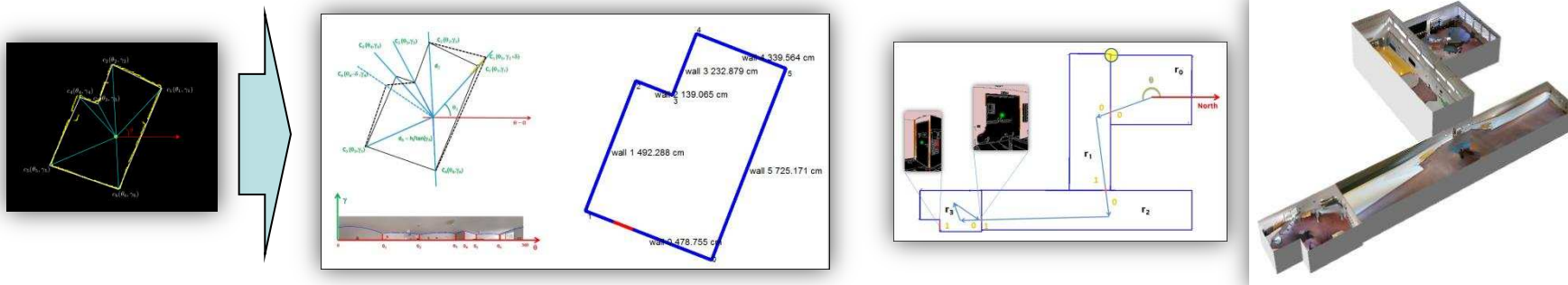
- **Analyze spheremap to extract single room structure**
 - Room model considers vertical walls
 - Extract edges and filter out regions likely far from top/bottom edges of walls
 - Find wall height
 - Voting scheme used to extract most likely wall height by maximizing pairs of matching wall-floor / wall-height edge pixels
 - Fit 2.5D room model to recovered wall edge map
- **Uses specialized transform to speed-up computation**



Vary h_w results in a transform scaling

Finding the rooms structure

- Iterated to map the entire floor-plan
 - Mobile tracking of user's direction moving between adjacent rooms creates a connected room graph
 - Doors position identification in the image by computer vision
 - Doors matching according with graph
 - Rooms displacement
 - Global optimization of combined model**



Pintore et al. Omnidirectional image capture on mobile devices for fast automatic generation of 2.5D indoor maps. IEEE WACV 2016

Results



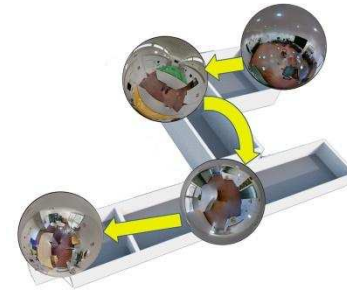
Scene Name	Features		Area error		Wall length error		Wall height error		Corner angle error		Editing time MagicPlan
	Area [m^2]	Np	MP	Ours	MP	Ours	MP	Ours	MP	Ours	
Office H1	720	10	2.95%	1.78%	35 cm	15 cm	2.0 cm	1.2 cm	0.8 deg	0.8 deg	26m32s
Building B2	875	25	2.50%	1.54%	30 cm	7 cm	6.0 cm	1.5 cm	1.5 deg	1.5 deg	42m18s
Commercial	220	6	2.30%	1.82%	25 cm	8 cm	12.0 cm	2.7 cm	1.5 deg	1.0 deg	28m05s
Palace	183	3	16.86%	0.20%	94 cm	5 cm	45.0 cm	1.3 cm	1.8 deg	0.5 deg	15m08s
House 1	55	5	21.48%	2.10%	120 cm	16 cm	15.0 cm	4.7 cm	13.7 deg	1.2 deg	25m48s
House 2	64	7	28.05%	1.67%	85 cm	8 cm	18.0 cm	3.5 cm	15.0 deg	0.5 deg	32m25s
House 3	170	8	25.10%	2.06%	115 cm	15 cm	20.0 cm	4.0 cm	18.0 deg	1.5 deg	29m12s

Pintore et al. Omnidirectional image capture on mobile devices for fast automatic generation of 2.5D indoor maps. IEEE WACV 2016

- Reasonable, fast reconstruction with rough structure and visual features

Sharing the indoor model

- **Indoor model**
 - Exploration graph
 - Each node is a spheremap/room
 - edges (yellow) are transitions between adjacent rooms
 - Stored on a server (standard http Apache2)
 - Panoramic images
 - Mapped according with the graph
- **Interactive exploration**
 - Room
 - **WebGL fragment shader**
 - dragging to change view orientation and pinching to zoom in/out
 - Passages
 - **Real-time rendering** of the transitions between rooms
 - Exploiting geometric model stored on the server
 - Performance improvement compared to use precomputed videos
 - Suggested paths

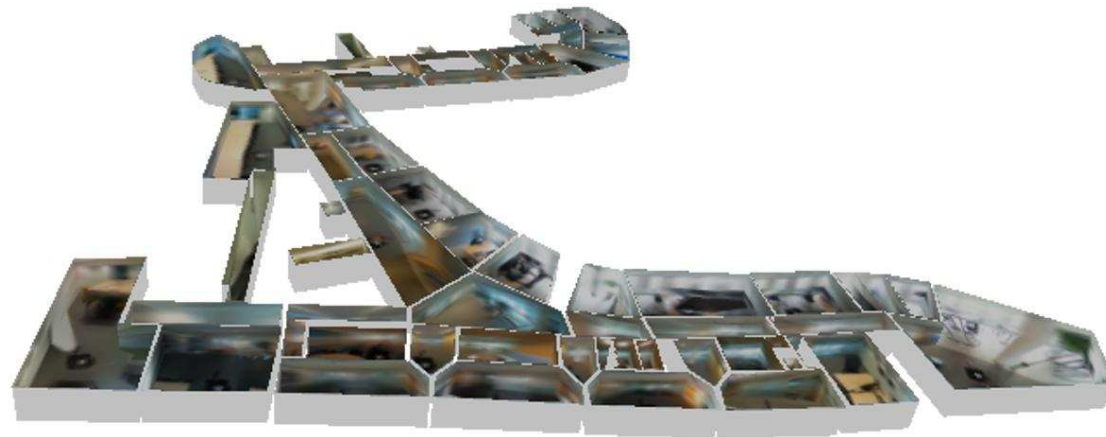


Some results

Live demo: <http://vcg.isti.cnr.it/vasco/>
[Click on the dataset on the left column to start](#)



3D reconstruction of a 655 mq office with 19 rooms.
 This environment was acquired with a mobile phone
 (HTC One M8)



Reconstruction of a 70 rooms floor of the NHV ministry at Den
 Haag, Netherlands. The whole model was acquired with a Ricoh
 Theta S camera

Next session:

CLOSING/Q&A

Part 6

All good things come to an end...

(Bad ones, too)

Subject: Mobile Graphics

- **All you need to know to get an introduction to the field of mobile graphics:**
 - Scope and definition of “mobile graphics”
 - Brief overview of current trends in terms of available hardware architectures and research apps built on top of them
 - Quick overview of development environments
 - Rendering, with focus on rendering massive/complex surface and volume models
 - Capture, with focus on data fusion techniques

Contacts (in alphabetical order)

- **Marco Agus (1,2)**
 - Research Engineer at KAUST (Saudi Arabia)
 - Researcher at CRS4 (Italy)
- **Enrico Gobbetti (1) - organizer**
 - Director of Visual Computing at CRS4 (Italy)
- **Fabio Marton (1)**
 - Researcher at CRS4
- **Giovanni Pintore (1)**
 - Researcher at CRS4
- **Pere-Pau Vázquez (3)**
 - Professor at UPC, Spain

(1) www.crs4.it/vic/

(2) <https://vcc.kaust.edu.sa>

(3) <http://www.virvig.eu/>



Funding...



**Center for Research,
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Saudi Arabia**



**Polytechnic University of
Catalonia,
Spain**



**Project TDM
RAS - POR FESR 2014-2020**



**REGIONE AUTONOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA
Projects VIGEC / VIDEOLAB**



**Spanish MINECO Ministry
FEDER funds
Grant No. TIN2014-52211-C2-1-R**

Thanks for your attention!

Q&A NOW (TIME PERMITTING...)

More information...



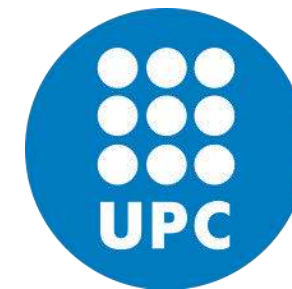
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**Polytechnic University of
Catalonia,
Spain**

www.virvig.eu